A Review of Emerging Video Codecs: Challenges and Opportunities

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Abstract—**This paper presents a review of video codecs that are in use and currently being developed, the codec development process, current trends, challenges and opportunities for the research community. There is a paradigm shift in video coding standards. Concurrently, multiple video standards are standardised by standardising organisations. At the same time, royalty free video compression standards are being developed and standardised. Introduction of enhancement-layer-based coding standards will extend the lifetime of legacy video codecs finding middle ground in improved coding efficiency, computational complexity and power requirements. The video coding landscape is changing that is challenged by emergence of multiple video coding standards for different use cases. These may offer some opportunities for coding industry, especially for New Zealand researchers serving niche markets in video games, computer generated videos and animations.**

Keywords—video coding, compression, MPEG, ITU, computational complexity, coding efficiency

I. Introduction

Video applications require acquisition, storage and transportation of picture data that have different characteristics compared to audio and text. Video data are generally captured at a high rate. Resource constraints in storage and transportation led to the development of methods to reduce the large quantity of video data per second for different applications. Television broadcasting has been transporting compressed video using radio frequencies over the air extensively. In recent times the applications of video have expanded enormously to include applications such as online video, surveillance, video calling, Internet of Things (IoT), augmented and virtual reality and video games. These applications require new structures and tools to compress video data. Current tools used in video coding are not adequate to reduce the ever-increasing raw video data rates from video capture with increasing spatial and temporal resolutions as well as wide colour gamut and high dynamic range. Increasing popularity of video games and video conferencing have presented new requirements to have new tools and structures.

Compression technologies are advancing at a rapid pace. These advancements are partly fuelled by advances in other areas such as artificial intelligence. Since MPEG-1, the adoption of a new generation of codecs was observed at regular time intervals. The standardisation process, harmonisation and management of intellectual property among competitive contributors are key activities for the success of a standard beyond its technical superiority. The collaborative work between International Telecommunication Union-ITU and ISO/MPEG led to the most common and affordable compression standard – Advanced Video Coding - AVC H264 or MPEG part 10. A similar collaboration led to high-efficiency video coding HEVC or H265 and Versatile Video Coding (VVC) or H266. Online or streaming service providers are also contributing to compression research in the areas of efficiency and performance evaluation. This paper briefly discusses and presents some of the research in developing next-generation codecs (VVC-Versatile Video Coding, EVC-Enhancement Video Coding, LCEVC-Low Complexity Enhancement Video Coding) and needs of the industry. However, those multiple codecs where some are royalty-free have disturbed the ecosystem. This is another disruption that broadcasters and media industry need to manage in business and digital transformation.

Compression technologies have been an enabler for the broadcast industry starting with analogue television. Over the last four decades, MPEG - Motion Pictures Expert Group - developed MPEG-1, MPEG-2, MPEG-4 and MPEG-H video compression standards. A given codec standard is developed with contribution from many researchers over a considerable time. International Standard Organisation/Motion Picture Expert Group - ISO/MPEG and International Telecommunication Union - ITU have harmonised and standardised them. The following sections discuss briefly the evolving video coding standards, standardisation process, advancements, trends and challenges.

For video coding standards, the core problem has remained the same: i.e. to reduce the size of stored or transmitted video data as much as possible while keeping the visual quality as close as possible to the original video. The convention when it comes to video coding standards has been to only define the bitstream format (syntax) and the decoder but not the encoder. This allows for cross-industry compatibility of the most critical component, i.e. the decoder, and at the same time it allows for innovation and flexibility in the design of the encoding process, for example, meeting requirements of latency and exploiting the availability of computational resources.

II. Evolution of Video Codecs

Video compression techniques and tools aim to reduce the size of a video by eliminating redundancies. The reduction in size results in lower bandwidth requirements and smaller storage needs. The tools that compress the video files or streams are called video codecs. Various codecs are being used in the broadcast and media industries. This section briefly introduces some of them.

Codec, which stands for *coder-decoder* is hardware, software, or combination that applies compression algorithms to the video. The algorithms search for and remove redundancies, thus reducing the amount of data; this can be the size of the file or bit rate if the video is streamed. There are four types of redundancy - spatial, temporal, statistical and

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colour space. For example, repetitive images or a background that repeats throughout a video are temporal and spatial redundant data.

Compression changes the original format of the video into a format supported by the video player or can be decoded by a standard decoder. The video codec determines the format of the video. There are two major classes of video compression, namely - lossy or lossless. Lossless compression, reduces redundant data without affecting quality, where the process maintains data integrity and is fully reversible. Unfortunately, lossless compression gives limited reduction in bit rate or file size of an image or video. Lossy compression, on the other hand, is able to give further reductions in file size or bit rate, at the expense of only being able to recover an approximation of the original source video. This commonly exploits perceptual coding (based on human perception) to make approximations such that they are less noticeable. However, the compression loses some data permanently, which affects the quality of the reconstructed image or video. If heavily compressed, the losses become noticeable resulting in annoying visible artefacts such as blockiness, blur, colour bleeding, and banding in the reconstructed image or video.

Video can be compressed using two stages: intra-frame and inter-frame. Intra-frame means that the codec compresses an individual frame. Inter-frame compression exploits redundant data between successive video frames. These are deployed in various codecs such as AVC or H264, VP9, HEVC and VVC.

MPEG-1 Video was the first MPEG standard that was completed in 1993 [1]. MPEG-1 was extensively deployed within Video CDs. MPEG-2 Video was completed in 1995 and became popular with the introduction of DVDs and digital TV broadcasting [2]. The MPEG-4 Advanced Video Coding (AVC/H.264) was completed in 2003. The primary applications of AVC were HDTV and internet-based video services such as Over-The-Top (OTT) and Video-On-Demand (VOD) [3]. MPEG-H High-Efficiency Video Coding (HEVC/H.265) was completed in 2013 [4]. HEVC has been deployed for 4K, high dynamic range (HDR) and wide colour gamut (WCG) video applications.

H264 (also known as AVC) is the MPEG-4 part 10 that was jointly developed by ISO-MPEG and ITU as the successor to MEPG-2. MPEG-2 is still being used by some countries that were early adopters of digital terrestrial television broadcasting services. From a wider industry perspective, AVC is still widely used though AVC is quite dated technology. The H.264 compression technology is available for almost every platform and device in the media market. AVC/H.264 is reaching a turning point where compression efficiency and speed can no longer be significantly improved. Therefore, many vendors of AVC/H.264 solutions are investing in pre-processing or layered compression add-ons to keep up with customer demand for premium visual quality. In a similar manner, introducing pre-processing or enhancement layer based coding standards will extend the lifetime of legacy codecs (codecs that have currently in use over a considerable period of time) such as AVC.

To meet these demands, several new video codecs have entered the market, such as HEVC/H.265, AV1 and VVC; each promising to deliver superior quality with unprecedented performance. The AVC standard has been upgraded with the High-Efficiency Video Coding (HEVC), or H.265, which is overtaking the previous version with the explosion of 4K video content. The H.265 has much higher data reduction efficiency in compressing videos and makes streaming of ultra-high-definition 4K or 8K videos easier.

A. Video Coding Standards

A video coding standard is a document describing a bitstream structure and associated decoding method for video compression. The standard defines the output structure that an encoder should produce rather than defining the encoder itself. This enables innovation in encoders. Generally, video coding standards define a set of tools for compression. Some of the tools are optional to be implemented to create a standard compliant bitstream. However, decoders conforming to the standard must implement a common minimal subset of compression tools.

Since the MPEG-1 standard, a wide range of video codecs have been developed. The majority of these have been developed and standardised by the International Telecommunication Union (ITU) Telecommunication sector and International Standardization Organization/ International Electrotechnical Commission (ISO/IEC). Those standards have been given an ISO/IEC identification under the Working Group 29 Motion Picture Expert Group (MPEG) such as MPEG-1, MPEG-2, MPEG-4, MPEG-H, MPEG-I, MPEG-5. Most of them have been developed jointly with ITU-T with identification H26X, where X currently goes from 1 to 6. Table 1 summarises some video coding standards.

TABLE I. MPEG VIDEO CODING STANDARDS

MPEG video coding standard	*Year*	*Known as*	*ITU-T*
MPEG-2 part 2	1998	MPEG-2	H262
MPEG-4 part 10	2003	AVC	H264
MPEG-H	2013	HEVC	H265
MPEG-I	2020	VVC	H266
MPEG-5 part 1	202x	EVC	No collaboration with ITU
MPEG 5 part 2	202x	LCEVC	No collaboration with ITU

The success of a codec can be measured based on how often it is used and the support available for the codec when it is deployed. H.261 was the first practical digital video coding standard that has shown its wide deployment in both information technology (IT) and communication fields. Subsequent international video coding standards (MPEG-1 Part 2, H.262/MPEG-2 Part 2, H.263, MPEG-4 Part 2, H.264/MPEG-4 Part 10, and HEVC) [9, 10, 11, 12, 13, 14, 15, 16] have been based closely on the H.261 design. Additionally, the methods used by the H.261 development committee to collaboratively develop the standard have remained the basic operating process for subsequent standardisation work in the field until recent time. However, now the video coding landscape is changing, this process is challenged by emergence of other coding standards such as AV1 and VP9 as royalty free codecs.

Since April 2018, a joint collaborative team of ITU-T and ISO/IEC experts known as the Joint Video Experts Team (JVET), which is a partnership of ITU-T Study Group 16 Question 6 (known as VCEG) and ISO/IEC JTC 1/SC 29/WG 11 (known as MPEG) have been working on the successor to

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HEVC: Versatile Video Coding (VVC), which is expected to see deployment in applications providing an immersive video experience such as virtual reality streaming, 8K broadcasting and high dynamic range (HDR) video. The quality target was more than 30% bitrate reduction compared to HEVC at the same perceptual quality. Although the codec will not be ready to deploy commercially until the end of 2020, some quality comparisons have already been done [27].

1) VVC (Versatile Video Coding):

The VVC codec is called versatile video codec because it has a number of capabilities that enable versatility. Among them are screen content coding tools (gaming, screen sharing), reference picture resampling (RPR - adaptive streaming), potential spatial scalability using RPR filters and independent sub-pictures (360 video, region of interest-ROI) [27].

The Joint Video Experts Team (JVET) established the Versatile Video Coding (VVC) and the VVC Test Model (VTM) algorithm description and encoding method. This document serves as a source of general tutorial information on the VVC design and also provides an encoder-side description of VTM.

VVC uses many new tools and methods to improve the coding efficiency. VVC has extended coding trees and block structure to accommodate efficient coding of pictures with unevenly spread spatial redundancy. As shown in Fig.1 and Fig 2, a data hierarchy can be developed using irregular blocks performed using recursive quadtree decomposition. This enables efficient block processing of spatial redundancies at the cost of managing the recursive tree structure.

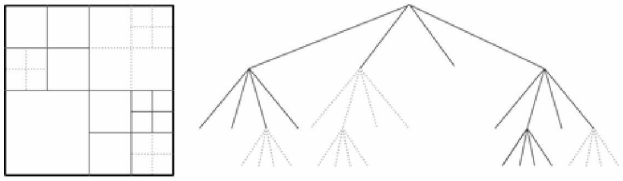

Fig. 1. Quad splitting of blocks and tree

Fig. 2. Quad Spliting of blocks and tree [Courtesy: © Fraunhofer HHI]

2) LCEVC (Low Complexity Enhancement Video Coding):

Traditional codecs encode and decode a single stream. LCEVC creates a hybrid stream with one lower resolution stream containing the base codec, which can be any codec, and an enhanced stream that provides additional resolution and quality. So, rather than encoding a 1080p stream using HEVC, an LCEVC encoder would create one backwards-compatible base layer stream using H.264 at for example 640×360 resolution, and a separate layer containing the additional data for native 1080p playback. LCEVC is a low-complexity codec that is in the process of standardisation as MPEG-5 Part 2. Instead of being an entirely new codec, LCEVC improves detail and sharpness of any base video codec (e.g., AVC, HEVC, AV1, EVC or VVC) while lowering the overall computational complexity, thus expanding the range of devices that can access high quality low-bitrate video. This is a paradigm shift in codec standards.

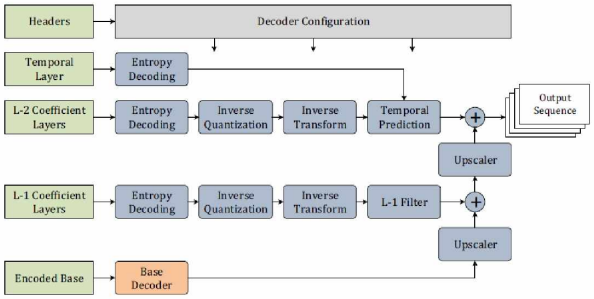

Fig. 3. Block diagram of LCEVC decoding

The concept is to use a base codec at lower resolution and add an additional enhancement layer of encoded residuals to mitigate artefacts. Details are encoded with a directional decomposition transform using a very small matrix (2×2 or 4×4) which is efficient at preserving high frequencies. As LCEVC uses parallel processing techniques to reconstruct the target resolution, it encodes video faster than a full resolution based encoder.

The codec is designed for use in conjunction with existing video codecs, leveraging specific tools for encoding residuals, i.e. the difference between the original video and its compressed representation. LCEVC can improve compression efficiency and reduce the overall computational complexity using a small number of specialised enhancement tools [7].

LCEVC allows for enhancement layers to be added on top of existing bitstreams. This is a useful application in Ultra High Definition video. The UHD resolution can be derived using High Definition and enhancement layers. The decoding can be shared between an ASIC and CPU. LCEVC can be decoded via light software processing, and even via HTML5. The compression quality and encoding complexity benefits are achievable with LCEVC as an enhancement to current H.264, HEVC and AV1 codecs.

As shown in Fig. 3, LCEVC has a data stream structure defined by two component streams, a base stream decodable by a hardware decoder, and an enhancement stream suitable for software processing implementation. The enhancement stream will provide new features such as compression capability extension to existing codecs, lower encoding and decoding complexity, for on-demand and live streaming applications.

The time taken to process the videos through the codec is also an important performance indicator for codecs beyond the compression gains. BBC research and development also tested processing time of codecs [6]. Increased processing times

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mean increased complexity, and therefore more computational power is required.

3) EVC (Enhancement Video Coding):

The MPEG-5 part-1 Essential Video Coding (EVC) standard is being developed by MPEG using a new process targeted at addressing business requirements, including licensing, as well as technical requirements, to facilitate rapid deployment and widespread use of the standard throughout the media industry. EVC addresses the needs that have become apparent in some use cases, such as video streaming, where existing ISO video coding standards have not been as widely adopted as might be expected from their purely technical characteristics.

EVC defines two separate profiles, the *Baseline profile* and *Main profile*. The Baseline profile contains only technologies that are older than 20 years or are otherwise freely available for use in the standard. The second profile adds a small number of additional tools, each of which can be either cleanly disabled or switched to the corresponding baseline tool on an individual basis.

4) Video Coding for Machines (VCM) Standard:

It has been proposed the next generation video codec called, video coding for machines (VCM), which provides compression coding for machine vision, as well as compression for human-machine hybrid vision. A new group (VCM group) has been created to establish a new standard that will improve the previous generation video coding and decoding standard H.26X. The VCM group will study the limitations that current video codecs present to video data that machines consume. The proposers aim to promote this new VCM standard rapidly, develop chips based on it and deepen the application for its broad use in the Internet of Things (IoT) ecosystem. This is a critical step for many industries, as for more than 40 years, MPEG has taken the global lead in producing mainstream digital media standards and enabled the development and success of digital media products, services and applications. From inception, MPEG has facilitated over 180 standards, including the well-known, H.264 (AVC), H.265 (HEVC) and H.266 (VVC) standards. The value generated by these essential MPEG standard patents with core codecs is quite high.

In addition to the Versatile Video Coding (VVC) that was released in July 2020, MPEG, ITU and the video coding industry have been working together to release a number of other codecs. Among them, the Network-Based Media Processing (NBMP), Video-based Point Cloud Compression (V-PCC), Essential Video Coding (EVC). Low Complexity Enhancement Video Coding (LCEVC) is expected to be released in October 2020, MPEG Immersive Video (MIV), Neural Network Compression for Multimedia (NNR) and Compression of Genomic Annotations is expected to be released in January 2021.

B. Video Coding Standardisation process

Standardisation enables interoperability where encoders and decoders from different developers and manufacturers to work together across a range of applications. However, standardisation needs to foster the maximum flexibility and encourage innovation. Hence, the standards do not include all practical issues and design techniques of the decoding process. Standardisation allows for decoding of bit streams from previous and emerging standards. The applications or users have a greater freedom to choose between manufacturers. The published standards provide a point of reference to developers of standard-compliant video coding systems. A compliant video codec has the capability to interoperate with other systems.

The standardisation process commences with a *Request for Evidence* (RfE). If there is adequate development potential to work on a new video coding standard as a successor to current state of the art video coding technologies, proposals are invited through a published *Request for Proposals* (RfP). However, only ITU-T members and MPEG members can make any proposal to the call. While this makes the process manageable, it does not allow an innovative researcher to propose directly. Proposals are then evaluated to select coding ideas to improve coding efficiency while maintaining practicality for implementation of encoder and decoder.

A reference software model to be developed and improved for any new codec prior to hardware or software implementation. Generally, the software model is improved a number of times over the development period prior to finalising the codec standard. The improvements to the test model are done until it reaches coding efficiency closer to expected, which is generally 30-50%. Then a complete suite of conformance streams is identified to validate a hardware design. This aims to eliminate any bug in the implementation algorithm. Finally, subjective verification tests also need to be carried out to understand the codec performance better.

C. Open Source and Proprietary Video CODECs

With rapid developments in Internet Protocol (IP) based video delivery, surveillance industry, Internet of Things (IoT) and computer-generated video industry, there are several video coding schemes in use today. Among the open source codecs are AV1 and VP9 which are currently royalty free video coding schemes developed by industry outside the MPEG or ITU video coding standardisation process.

AV1 is an open source codec from Alliance for Open Media (AOM), whose members include Amazon, Apple, Facebook, Google, Microsoft, Cisco, Intel, IBM, Netflix and Samsung, among others. It was launched in 2018, and over time it has shown some improvements in encoding time and decoding efficiency [5]. AV1 currently has comparable coding efficiency to HEVC [27]. However, it has not shown considerable encoding efficiency compared to VVC [27].

VP9 is an open-source codec that was developed by Google offering better performance than H.264 but doesn't support live streaming as of yet. It produces more reliable and consistent streams with a much smaller file size compared to H.264 that is also easy to stream over the Internet.

III. New Coding Tools

There are over thirty (30) video compression tools that will contribute to overall compression efficiency gains. Following are some of the tools that are available on compression standards such as versatile video coding [7, 8]. Due to limited space each tool cannot be explained. However, some tools are described with reference to applications.

:

1. Flexible Block Partitioning with Multi-type Tree (MTT)
2. Separate Tree for Luma and Chroma (CST)
3. Dependent Quantization (DQ)
4. Multiple Transform Set (MTS)

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5. Low Frequency non-separable transform (LFNST)
6. Adaptive Loop Filter (ALF)
7. Joint coding of chrominance residuals (JCCR)
8. Bi-prediction with CU weights (BCW)
9. Decoder-side motion vector refinement (DMVR)
10. Symmetric motion vector difference (SMVD)
11. Sub-block transform (SBT)
12. Combined intra/inter prediction (CiiP)
13. Multi-reference line intra prediction (MRL)
14. Intra block copy mode (IBC)
15. Affine Motion Compensation (AMC)
16. Subblock-based Temporal Merging Candidates
17. Adaptive motion vector resolution (AMVR)
18. Triangular partition mode (TPM)
19. Bi-directional optical flow (BDOF)
20. Merge with MVD (MMVD)
21. Intra sub-partitioning (ISP)
22. Matrix based intra prediction (MIP)
23. Cross-component Linear Model (CCLM)
24. Luma mapping with chroma scaling (LMCS)
25. Transform Skip Residual Coding (TSRC)
26. Quantized residual DPCM

IV. Challenges related to Video Codecs

Traditionally, the development cycle of a codec starts with observing potential to develop, call for evidence, call for proposals followed by recursive process of improving a model until features are frozen to implement mainly in hardware and software and hybrid implementation. In this process, video coding experts from all over the world spend many hours over its development cycle, which usually spans a number of years (often up to ten years). Once a codec is developed, enormous investments have had been made by contributing organisations and individuals. For the process to go on, the organisations need to recover that investment to sustain further research and development. Having multiple codecs, which are specific to some applications make cost of development, especially when it is an ITU-MPEG standard, per codec higher. However, it will be less than a proprietary codec due to economies of scale.

A. Royalty and licensing issues

Currently industry presumes that AV1 will be free of royalty. However, to a great degree, the codec future will be decided by AV1's royalty-free status, which AOM could secure by proving that member companies truly reinvented the wheel with AV1 or by licensing technology as needed. In 2013, Google hindered the formation of a common patent pool for its codec VP8. For the success of AV1 AOM as collectively need to gain enough control over AV1's intellectual property (IP) rights to distribute AV1 with a fair and reasonable royalty. Many of the intellectual properties of AV1 are owned by the organisations which developed H.264, HEVC, and VVC. If individual contributors attempt to hold on to IP without licensing both royalty free and future MEPG codecs will suffer from low penetration to the video market.

V. Trends and Opportunities Offered by New Codecs

Artificial intelligence (AI) is shaping many industries by offering efficient solutions. AI and coding innovators are proposing various approaches to address video compression issues. Traditional video compression requires a considerable amount of skill, time, and effort. Applying machine learning addresses some of these challenges by automating the processes. Machine learning (ML) can be used to gain:

(i) Development savings: video codecs are complex algorithms. Developing a video codec may take a long time even with a large number of researchers. Machine learning software shortens the process since the software learns and adapts the algorithms, with little human intervention.

(ii) Improve encoders density: some ML implementations require less computing power than other algorithms. Many ML algorithms are implemented using the processing power of Graphical Processing Unit (GPU), instead of the Central Processing Unit (CPU). GPUs have multiple smaller logical cores than CPUs, which enables them to process simpler computations in parallel. GPUs are well suited for image and video processing with the coordination of the CPU as a controller.

The AI-based video compression is forming some trends. Two of them are:

(i) Customisation: while today compression tools are generic, it is possible that in the near future compression algorithms can be customised, as they evolve at a rapid pace.

(ii) Auto-encoders: one of the applications of neural networks to video compression has led to the development of auto-encoders. Auto-encoders are artificial neural networks that learn a compressed input and then reconstruct it without supervision. This is especially useful for the field of video compression.

Video compression technology is accelerating its development with the deployment of machine learning algorithms. As video streaming is gaining popularity, the number of videos online grows exponentially, and increased access have led to need for AI-based compression. For a long time, machine learning video compression has been the basis of AI-based compression. Now with deep learning, more advanced AI-based compression can be deployed. Algorithms with neural networks may enable video compression technologies reach a new and improved level.

VI. Conclusions

The future of multi-codec in video communications has both advantages and disadvantages. Though application specific codecs with higher coding efficiency and lower implementation complexity may emerge, they may cost more due to lack of economies of scale in royalty fees.

Rapid development of a wide range of video codecs are introducing challenges to the industry and consumer. The industry may end up with multi-codec adaptation.

An innovative researcher, organisation or start-up could offer their intellectual property to a larger organisation such as Google, Netflix or any encoder developer as this has been the case during the last decade.

VVC and EVC increase encode and decode complexity so most implementations will require hardware support. This will introduce delay as chip vendors and device vendors need time to implement the new technology. Video hardware industry would like to see a high level of certainty in licensing costs prior to embarking on implementations. That confidence is as important as superior coding efficiency gains for the successful deployment of new video codecs.

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As LCEVC has a royalty free layer, it can be immediately implemented in software. It is also backwards compatible which further simplifies deployment. This enables online video services such as Over-the-Top (OTT) to deploy LCEVC without hardware support carrying out any enhancement layer processing in software.

A key factor in the successful deployment of a new video codec standard is the support of the consumer industry. The proponents of the EVC standard are major players in the mobile market, which is the most dynamic in terms of device renewal, video consumption and mobile network stress, making EVC an enabler.

LCEVC is a codec-agnostic tool that can significantly enhance the compression efficiency of any video codec, both existing (AVC/H.264, HEVC, VP9) and emerging (AV1, EVC, VVC) whilst reducing the processing requirements of encoding and maintaining compatibility with the ecosystem of decoders of the enhanced codec.

VII. Future Work

In a future study, authors will address the evaluation of video compression, new tools, methods, limitations and automation.

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