EXPLORING THE BENEFITS OF DYNAMIC RESOLUTION ENCODING AND SUPPORT IN DVB STANDARDS

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ABSTRACT

In 2015, Netflix introduced Per-Title Encoding Optimization, defining the best resolution for a title at a given bitrate. Since then, Netflix has improved its algorithms to make the technique more dynamic through scenes and has deployed it for VOD applications to enhance bandwidth use and video quality. Thanks to recent developments in AI, Dynamic Resolution Encoding (DRE) can now be applied to live applications with very limited extra CPU consumption.

This paper will explain why DRE is not a feature limited to new codecs, such as VVC or AV1 and can also be applied to legacy codecs, like AVC or HEVC, for streaming applications. It will present concrete results of experiments that apply DRE on top of the AVC, HEVC or VVC codec for broadcast (TS) and broadband (DASH/HLS), examining how DRE can leverage the compression power of such a codec to reduce HD or UHD 4K bandwidth, improve video quality, and reduce power consumption.

In addition, the paper will report on the interoperability results with DVB-T2 UHD TVs as well as with DVB DASH players. It will conclude with the latest development of DVB standards to support DRE.

INTRODUCTION

Video compression experts all know that when bandwidth is reduced, a good trade-off to preserve quality and limit visible compression artifacts is to reduce the resolution. Of course, the best resolution for a given bitrate highly depends on the video content. In December 2015, Netflix popularized the concept of variable resolution encoding, in its blog “Per-Title Encoding Optimization” [1]. At the time, the best resolution was selected for each VOD content. In the following years, Netflix improved the concept with Dynamic Resolution Selection, applied for each scene. As Netflix’s market is VOD, this selection can be made offline, but a viewing-based selection would be much too time consuming. To mitigate this issue, Netflix developed an objective video quality (VQ) metric, called VMAF, to help in the resolution selection process automation. More recently, Fraunhofer FOKUS made use of AI to build optimized encoding ladders per scene, leading to significant bandwidth and storage savings [2].

Harmonic has implemented a similar concept on live content with a very dynamic selection, applied for each video delivery segment of a few seconds duration. The first section explains how the Dynamic Resolution Encoding can work in a live workflow. The second section presents the possible use cases and why its application is not limited to new codecs. The third section presents concrete results of experiments that apply DRE on top of the AVC, HEVC or VVC codec for broadcast (TS) and broadband (DASH or HLS). The next section goes through the results of interoperability evaluation with DVB-T2 UHD TVs as well as with DVB DASH players. The last paragraph concludes with the latest development of DVB standards to support DRE.

DYNAMIC RESOLUTION ENCODING FOR LIVE VIDEO DELIVERY

The per-scene encoding optimization from Netflix makes use of multiple encodings as well as resolution selection based on real VQ measurement, as shown in

Figure 1. For live streaming, this solution would be much too computationally intensive and would result in too much delay.

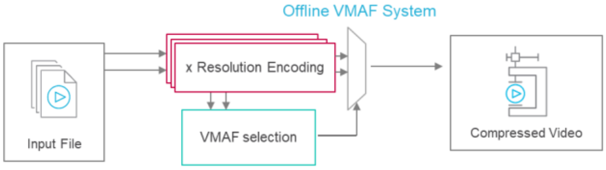

Figure 1: VOD Dynamic Resolution Encoding

Harmonic has been working intensively on AI-based compression for a few years [3] and has been addressing the resolution selection problem in a live environment. A live encoding system is characterized by a limited look-ahead of picture analysis before encoding and delivery stages. Therefore, it is not realistic to take a decision for a global scene that can be of a variable duration. Instead, a very dynamic decision scheme is built with a selection of resolution applied for each video segment of limited duration (typically two to three seconds). Spatial and temporal characteristics of the input video produced in the pre-analysis stage of the encoder have been used as features to train a ML-based prediction model, offline, in a supervised learning environment, as shown in Figure 2 below. Each video segment is encoded with various resolutions at a given target bitrate (constant or capped bitrate). At run time, using the appropriate video characteristics from the pre-analysis stage and the same target bitrate, the live encoder can decide on the best resolution to encode the pictures of the current segment by using the prediction model created offline. The best resolution is the one that provides the best visual quality.

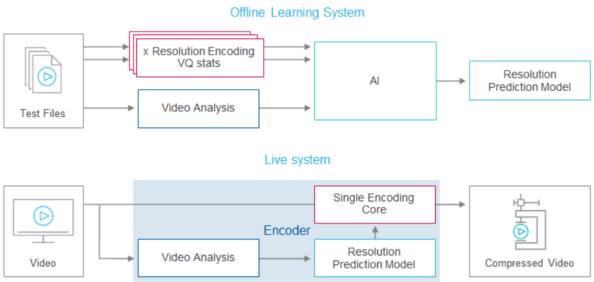

Figure 2: AI-based Live Dynamic Resolution Encoding

The increase of processing complexity is very limited since the prediction model is a decision tree algorithm driven by features that were already computed. The additional delay is, as always, a trade-off with quality. A pre-analysis of the full segment duration can better tackle a change happening in the last part of the segment but would add a significant delay. The use of the classical look-ahead adds no delay but takes the decision on the first part of the segment and may react to a change with one segment delay. One way to limit the impact is to work with segments of variable duration to align them with scene characteristics changes. These changes may not only happen at scene cuts but also within a scene when there is a change in the way the scene is captured (camera pan start or stop) or when significant objects move in the scene.

Dynamic Resolution Encoding Application and Use Cases

A common misperception is that only new codecs, like VVC or AV1, allow resolution changes within a video stream, with new tools like Reference Picture Resampling. That is simply not true, since an AVC or HEVC stream can implement resolution changes as far as the new group of pictures (GOP) is encoded independently from the previous group of pictures. That is what is called closed-GOP conditions and is typically achieved when an IDR picture is inserted. Any AVC or HEVC decoder will support the resolution change at IDR boundaries, but the "tricky" part is the automatic and seamless upscale to the display resolution.

What we call DRE in this paper is a change of resolution at IDR boundaries, even for the VVC case. Reference Picture Resampling, by allowing resolution changes between the reference pictures and the pictures to be predicted, may provide compression gains thanks to the use of open-GOP conditions as well as an adaptive resolution for pictures within the GOP. These gains have not been evaluated in our study, and the freedom in the setting of resolution within the GOP will have to be qualified with specific interoperability tests.

The first use case of Dynamic Resolution Encoding (DRE) that comes to mind is OTT streaming with the most widely used DASH and HLS delivery formats, since OTT players are used to playing dynamically with representations that can be of various resolutions. In this type of delivery, a ladder of profiles with various bitrates and resolutions is built for video encoded representations so that the client can adapt to the bandwidth fluctuations by requesting the appropriate representation. Today, the ladders of live OTT streaming are built using average statistics of best resolution per bitrate and do not take into account the individual video content characteristics. The resolution usually decreases with the profile bitrates. With a DRE scheme, the same maximum resolution can be set for all profiles and the resolution used for a video segment will vary within a given bitrate profile depending on video characteristics. The DRE can be set for all or selected bitrate profiles.

Use of DRE approach can result in:

- bandwidth savings for the same QoE by using a lower constant (CBR) or capped (cVBR with Content Aware Encoding) bitrate for the highest profiles thanks to a lower resolution when the content is too challenging for the highest resolution,
- a better QoE (higher sharpness) of static scenes with details by using a higher resolution at any bitrate profiles,
- a better QoE (less compression artifacts or higher sharpness of edges) of temporally complex scenes by using a lower resolution at the highest bitrate profiles, because a lower quantization better preserves the content,
- storage savings by reducing the number of profiles for the ladder,
- CPU savings by lowering the resolutions for the most complex scenes on the highest profiles and by reducing the number of profiles.

A better QoE thanks to a higher resolution on static scenes will happen not only on the lowest bitrate profiles where the resolution has been previously set at a low level but also at the highest bitrate profiles, where DRE can give the opportunity to launch higher resolutions like 2560x1440p or even 4K, while the live OTT streaming ladder has often been limited to 1080p up to now.

The implementation of DRE depends on the OTT delivery format. With DASH-based OTT streaming, the manifest indicates the resolution of the content for each representation with the two parameters height and width. If DRE had to be used at a larger scale, some addition in the MPEG DASH standard [4] or in the DASH-IF IOP [5] may be included to mention more specifically that these height and width information correspond to the max possible resolution. To make sure the decoder in the OTT player can properly handle such a stream, the video representations will have inband signaling of resolution using avc3 MP4 brand for AVC, hev1 MP4 brand for HEVC and vvi1 MP4 brand for VVC in the MP4 container. This means that the player/decoder will get the resolution from the high-level syntax of the encoded stream. When being served with a lower resolution than the one indicated in the manifest for the requested profile, the player/decoder will decode it and upscale to the nominal resolution set in the manifest.

The HLS specification [6] describes the resolution element in the manifest by saying “The value is a decimal-resolution describing the optimal pixel resolution at which to display all the video in the variant.” This is therefore not a description of the actual segment resolution and there is no need to change anything in the HLS specification.

For HLS-based OTT streaming, one initialization file per resolution is created. Each time the resolution changes, a #EXT-X-MAP tag with reference to the proper initialization file is added in the playlist. This scenario is possible because HLS implies, per construction for live content, a dynamic playlist updated at every new segment be made available on the origin. The video representations can have classical out-of-band signaling using avc1 MP4 brand for AVC, hvc1 MP4 brand for HEVC, vvc1 MP4 brand for VVC in each segment or an inband signaling of resolution: avc3 MP4 brand for AVC, hev1 MP4 brand for HEVC, vvi1 MP4 brand for VVC in the MP4 container as described for DASH delivery. The latter option allows common segments for both DASH and HLS delivery.

DRE can also be applied to broadcast delivery, where the use of a lower resolution on temporally complex scenes can result in bandwidth and CPU savings. The traditional way of adapting the encoding scheme to the video content characteristics for the broadcast delivery was to share the bandwidth of a transponder among multiple video channels and to allocate a bitrate to each channel in function of the content characteristics in a very dynamic way, using a statistical multiplexing engine.

With a segment-based IP broadcast as specified by ATSC 3.0, with a DASH segment being serialized using ROUTE protocol, the dynamic allocation of bitrate may be constrained much more than what could be possible in a shared transponder. Therefore, DRE can be of high interest to preserve QoE in this constrained environment as well as to reduce the transponder cost. In Brazil, the SBTVD Forum has selected DRE as a possible enhancement to the VVC-based TV 3.0 standard for the new broadcast system, which will be deployed in 2024 and onward [7]. Our tests have shown that the 4K resolution could be used, even at a very low bitrate of 5 Mbps. An ATSC 3.0 DRE HEVC-based system was demonstrated by Harmonic at the 2022 NAB Show at the Ultra HD Forum booth, using a Sony ATSC 3.0 TV. [8]. This demo showed that a bitrate of 9 Mbps is high enough to provide a good QoE for an outdoor sports sequence, mixing scenes of various spatial and temporal characteristics, thanks to an adaptive resolution from 4K to 1080p.

Even for a traditional TS-based broadcast making use of statistical multiplexing, DRE can have a value by smoothing the peak bitrate requests since the usage of a lower resolution for the most complex scenes will result in lower bitrate needs for the same QoE. It will provide a better QoE for congestion cases where all channels are complex at the same time. This can happen even more when the number of channels is small in the transponder, which is more frequent when broadcasting UHD channels. Therefore, DRE can favor the development of UHD channels. Though, if resolution changes are authorized at closed-GOP boundaries with legacy codecs, no constraint is given in the DVB specification on the seamless switch support for the TS-based Integrated Receiver Decoder (IRD) and interoperability needs to be checked.

Video Quality Evaluation Results

We considered three use cases with different codecs and maximum resolution:

- a 1080p59.94 AVC delivery @ 4Mbps, with 1080p, 720p and 540p resolutions,
- a 4K 59.94 HEVC delivery @ 7Mbps, with 2160p, 1440p, 1080p and 720p resolutions,
- a 4K 59.94 VVC delivery @ 5Mbps, with 2160p, 1440p, 1080p and 720p resolutions.

We took outdoor sports content (regatta) in 4K HDR PQ BT.2020 @ 59.94fps format. This content is of one minute duration and provides scenes of various complexities. The lower resolutions were produced using a Lanczos filter. We converted the HDR content into SDR BT.709 using a proprietary HDR-to-SDR converter, since Harmonic's AI resolution selection model or VMAF measures work for SDR content right now.

We segmented the video content using segments of two seconds duration, whatever the delivery format (TS, DASH, HLS) was. We selected the best resolution for each video segment.

We used Harmonic's AI resolution selection and real-time encoding engine to produce the AVC and HEVC DRE streams, and an offline encoding engine and VMAF measurements to produce the VVC stream.

The subjective evaluation of the video quality was performed by three Harmonic experts on a 65-inch OLED 4K TV from LG, during daytime, avoiding artificial light and sunlight. We performed our tests in two steps:

- First, we watched the DRE streams to check the global quality.
- Second, we built split screens streams comparing the stream encoded at a constant full resolution (1920x1080p or 3840x2160p) with the DRE stream up to the same resolution, using FFMPEG cropping and re-encoding at a high bitrate to preserve initial qualities, as shown in Figure 3 below.

Figure 3: 1080p/DRE or 4K/DRE split screen

HD AVC Use-case

In this use case, the content is delivered at a constant and challenging bitrate of 4Mbps and can make use of one of the three following resolutions: 1920x1080p, 1280x720p or 960x540p.

Figure 4 shows the shares of resolution choices:

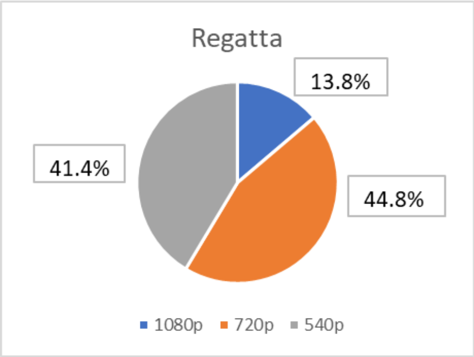

Figure 4: AVC resolution selection shares

We can observe that there is a good variety of resolution choices at this bitrate. The resolution may change within a scene when the video characteristics change (typical case of a camera pan). The subjective evaluation shows that there is no perception of resolution changes within a scene. The comparison with the encoding at the constant 1080p resolution shows that a reduction of artifacts is perceived on complex scenes, thanks to DRE. No bad choices of resolution (no significant loss of details or sharpness) are observed.

To determine what the DRE bandwidth savings can be, we made the same split screens comparing the @ 4 Mbps DRE stream with the constant resolution 1080p stream @ 5Mbps (20% savings) and 6 Mbps (33% savings). The subjective evaluation showed that close to 33% bitrate savings can be achieved.

Table 1 shows the average VMAF score, the best VMAF gain of DRE on a segment compared with 1080p encoding and the associated VMAF score for that segment.

Content	Average VMAF	Best DRE VMAF gain	Associated VMAF for best DRE gain
Regatta	75.73	+13.06	62.84

Table 1: VMAF measurements of DRE stream vs 1080p

Up to +13 VMAF points can be achieved using a lower resolution and the best gains are obtained on the segments where the VMAF scores are much lower than the average VMAF score on the sequence, which proves that DRE is important to preserve the quality on the most complex scenes.

UHD HEVC Use-Case

In this use case, the content is delivered at a constant and challenging bitrate of 7 Mbps and can make use of one of the four following resolutions: 3840x2160p, 2560x1440p, 1920x1080p or 1280x720p.

Figure 5 below shows the shares of resolution choices:

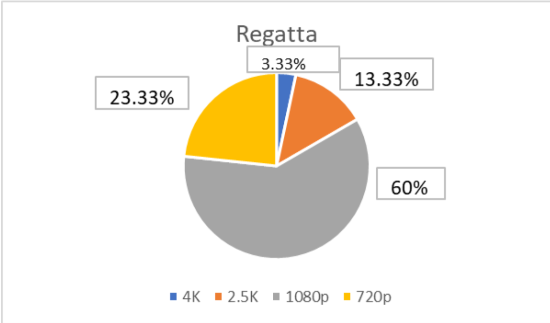

Figure 5: HEVC resolution selection shares

We can observe that there is, once again, a good variety of resolution choices at this bitrate. The resolution may change within a scene when the video characteristics change (typical case of a camera pan). The subjective evaluation shows that there is no perception of resolution changes within a scene. The comparison with the encoding at the constant 4K resolution shows that a reduction of artifacts is perceived on complex scenes, thanks to DRE. No bad choices of resolution (no significant loss of details or sharpness) are observed.

To determine what the DRE bandwidth savings can be, we made the same split screens comparing the @ 7 Mbps DRE stream with the constant 4K stream @ 9 Mbps (22% savings) and 10 Mbps (30% savings). The subjective evaluation showed that ~20% bitrate savings can be achieved, since the DRE stream quality @ 7 Mbps is close to the 4K stream @ 9 Mbps.

For each DRE stream, Table 2 shows the average VMAF score, the best VMAF gain of DRE on a segment compared with 4K encoding and the associated VMAF score for that segment.

Content	Average VMAF	Best DRE VMAF gain	Associated VMAF for best DRE gain
Regatta	85.77	+8.95	87.57

Table 2: VMAF measurements of DRE stream vs 4K

Up to +9 VMAF points can be achieved using a lower resolution and the best gains are obtained on the segments where the VMAF scores would have been much lower than the average VMAF score on the sequence, which proves that DRE is important to preserve the quality on the most complex scenes.

UHD VVC Use-Case

In this use case, the content is delivered at a constant and challenging bitrate of 5 Mbps and can make use of one of the four following resolutions: 3840x2160p, 2560x1440p, 1920x1080p or 1280x720p.

Figure 6 below shows the shares of resolution choices:

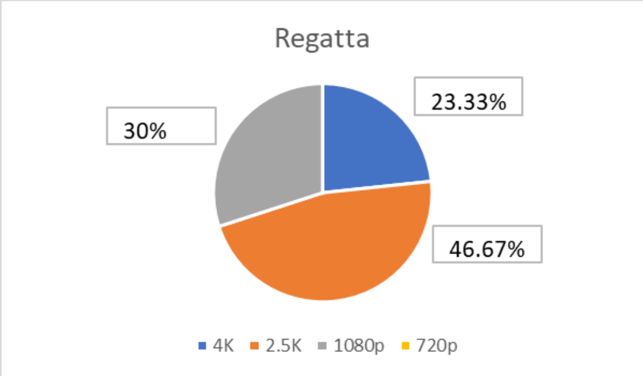

Figure 6: VVC resolution selection shares

We can observe that there is, once again, a good variety of resolution choices with an increasing use of 4K compared to HEVC. The resolution may change within a scene when the video characteristics change (typical case of a camera pan). The subjective evaluation shows that there is no perception of resolution changes within a scene. The comparison with the encoding at the constant 4K resolution shows that a slight reduction of artifacts is perceived on complex scenes, thanks to DRE. No bad choices of resolution (no significant loss of details or sharpness) are observed.

To determine what the DRE bandwidth savings can be, we made the same split screens comparing the @ 5 Mbps DRE stream with the constant 4K stream @ 6Mbps (16.66% savings) and 7 Mbps (29% savings). The subjective evaluation showed that bitrate savings are below 16.66% since the DRE stream quality is slightly lower than 4K stream quality @ 6 Mbps on two scenes.

For each DRE stream, Table 3 shows the average VMAF score, the best VMAF gain of DRE on a segment compared with 4K encoding and the associated VMAF score for that segment.

Content	Average VMAF	Best DRE VMAF gain	Associated VMAF for best DRE gain
Regatta	86.35	+3.3	77.91

Table 3: VMAF measurements of DRE stream vs 4K

Up to +3.3 VMAF points can be achieved using a lower resolution and the best gains are obtained on the segments where the VMAF scores are much lower than the average VMAF score on the sequence, which proves that DRE is important to preserve the quality on the most complex scenes. We can observe though that DRE has a lower gain on VVC compared with HEVC. The explanation we can give is that VVC may be more efficient in its adaptation to the encoded resolution by using more flexible block sizes and therefore is less impacted by the benefits of using a lower resolution. Though, care must be taken with these measurements since we have no hindsight on the pertinence of VMAF measurements for VVC streams.

CPU Savings Results

In addition to the bandwidth savings or QoE improvements, DRE also brings non-negligible CPU savings as the CPU cycles decrease when encoding lower resolutions. On the AVC HD use case @ 4Mbps, 40% CPU savings can be achieved compared with encoding at a constant 1080p resolution. On the HEVC 4K use case, close to 60% CPU savings can be achieved compared with encoding at a constant 4K resolution. On the VVC test set, close to 40% CPU savings can be achieved compared with encoding at a constant 4K resolution.

Reduced global power consumption in the headend, associated with significant bandwidth savings for the storage and delivery of video streams, make AI-based DRE technology the perfect solution for addressing the requirements of decreasing carbon footprint in the coming years.

The impact of DRE on consumer receivers embedded with hardware video decoding chips will not be as high as what is measured on the headend side, but even if the energy savings is limited to 10% to 15%, it can have a huge impact on reducing the global carbon footprint, considering the number of video decoding devices in use.

Interop Test Results

Streams using a dynamic resolution have been tested with the following devices:

- DASH and HLS players,
- DVB-T2 4K TVs.

DASH AVC DRE streams with inband signaling of resolution are well supported by the reference dash.js and Shaka players in Edge or Chrome browsers. DASH HEVC streams with inband signaling are well supported by the reference Shaka player in the Edge browser and by an exoplayer-based player running in Android devices (STBs or tablets). Though, tests made by DVB members with DASH players used in consumer products (TVs or STBs) already deployed did not confirm perfect support. Some jitters or glitches were noticed at resolution transitions.

HLS HEVC DRE streams with inband signaling when accessed through a playlist that refers to the right Init file each time the resolution changes are well supported by the iPad using the native player in Safari and the Shaka player in Edge browser. Since the playlist refers to a new Init file each time the resolution changes, the fragmented MP4 file may not require inband signaling. At the time of writing this article, this test has not been done yet. HLS AVC streams have not been tested either.

The HEVC DRE stream has been encapsulated into TS for DVB-T2 tests. Tests made with recent 4K TV sets of major brands (2020/2021 models), in collaboration with TDF in France, showed that the stream is well supported but with a few black frames (often below 100 ms) on many TVs when the resolution changes in the stream. Only one TV set was close to a seamless behavior with a one-frame freeze. Tests made by DVB members on seven TVs from various manufacturers showed the same black frames, up to 1s, and some failed more spectacularly.

DVB Standards Development

The DVB TM-AVC group in charge of the writing of technical specifications is currently updating the TS 101 154 specification for the use of Video and Audio Coding in Broadcast and Broadband Applications to add new codecs like VVC and AVS3 for the time being. It might possibly add AV1 later.

The question of the support of dynamic resolution changes has been brought to the group by Harmonic not only for these new codecs but also for legacy AVC and HEVC codecs.
For broadcast applications, the short black issues observed on nearly all DVB-T2 4K TVs deployed on the market make Dynamic Resolution Encoding unapplicable at the required high frequency changes of resolution. Therefore, DVB does not plan to update its specification for requesting seamless support of DRE using AVC or HEVC codecs.

For OTT streaming applications, many DASH players running in deployed consumer products were conceived by considering that the resolution can never change within a representation and do not perform a seamless upscale to the display resolution. This is clearly a limitation on the TV set side, as they are also able to support dynamic resolution changes with the Netflix app. Additional tests are being carried with the chipsets equipping those TVs, and more interop tests will be needed to better understand the TV sets limitations. For the time being, DVB is reluctant to update its DVB-DASH specification for requesting seamless support of DRE within video representations encoded with AVC or HEVC codecs, until there is a stronger market demand. Our feeling is that this market demand could grow in the near future because nothing will prevent OTT apps, such as Netflix, from deploying the DRE technology for live as it has already done for VOD applications. Without an update of DVB specification, the horizontal market would not be able to leverage this technology breakthrough and therefore it would put broadcasters, again, at a disadvantage vs. OTT providers.

For new codecs, like VVC, DVB is keen on supporting resolution changes within the stream, even in an open-GOP approach, thanks to new mechanisms like VVC Reference Picture Resampling (RPR) but would allow resolution changes at Random Access Points (RAP) only and not at any picture.

CONCLUSIONS

The tests we made on three different use cases (i.e., HD AVC, 4K HEVC, 4K VVC) show that DRE can push the boundaries of video compression by preserving the quality of complex scenes at lower bitrates thanks to the use of a lower resolution while keeping the sharpness of pictures with the highest possible resolution on static scenes with details.
At the same bandwidth, when the bitrates are challenging, the DRE offers better quality than encoding at the highest resolution as demonstrated by the split screens between constant resolution and DRE streams. The subjective assessments are confirmed by objective VMAF measurements, which show a significant gain brought by the DRE for the most complex scenes. In addition to bandwidth savings, DRE can bring significant CPU savings compared with encoding at a constant HD or 4K resolution.
DRE could also be used to increase the VQ/QoE by allowing the use of higher resolutions, like 4K or 1440p, in a limited bandwidth.

DRE can boost live OTT streaming experiences by building content-aware dynamic profiles instead of constant profiles based on average statistics, as done currently. This will lead to bandwidth savings, better QoE, storage and CPU savings. Interoperability tests performed within DVB with legacy DVB DASH HEVC players did not show seamless support, and DVB has not yet decided to update its specification to require the support of DRE profiles in DVB DASH AVC or HEVC players. However, our tests showed that DRE is well supported by reference DASH or HLS players, and nothing prevents major OTT operators from mandating the support of DRE through a software update of AVC/HEVC DASH/HLS players running in the most popular deployed devices.

For more traditional broadcast delivery, such as DVB-T2 systems, the interoperability tests showed that resolution changes at a high frequency would require a software update of deployed DVB-T2 4K TVs that is not realistic, and DRE will preferably target future VVC-based broadcast deployments.

Other broadcast networks such as IPTV, DTH and QAM could also be considered, but the variety of clients and the lack of DVB standardization for resolution change does not make us confident this path could be pursued.

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