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| **INTERNATIONAL ORGANIZATION FOR STANDARDIZATION ORGANISATION INTERNATIONALE DE NORMALISATION ISO/IEC JTC 1/SC 29/WG 5 MPEG JOINT VIDEO EXPERTS TEAM WITH ITU-T SG 16** |
| **ISO/IEC JTC 1 / SC 29 / WG 5 N 224** |
| **Geneva, CH, 11–19 July 2023** |
| |  |  | | --- | --- | | **Title:** | **Preliminary working draft 3 of TR: Optimization of encoders and receiving systems for machine analysis of coded video content** | | **Source:** | **Convenor (Jens-Rainer Ohm)** | | **Type:** | **Project** | | **Subtype:** | **Draft** | | **Status:** | **Approved** | | **Date:** | **2023-09-14** | | **Expected Action:** | **Info** | | **Action due date:** | **N/A** | | **No. of pages** | **12** (without this cover page) | | **Email of convenor:** | **ohm @ ient . rwth-aachen . de** | | **Committee URL:** | **https://sd.iso.org/documents/ui/#!/browse/iso/iso-iec-jtc-1/iso-iec-jtc-1-sc-29/iso-iec-jtc-1-sc-29-wg-5** | |

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| **Joint Video Experts Team (JVET)**  **of ITU-T SG 16 WP 3 and ISO/IEC JTC 1/SC 29**  31st Meeting, Geneva, CH, 11–19 July 2023 | Document: JVET-AE2030-v1 |

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| --- | --- | --- | --- |
| *Title:* | **Optimization of encoders and receiving systems for machine analysis of coded video content (draft 3)** | | |
| *Status:* | Output document by JVET | | |
| *Purpose:* | Output document | | |
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# Abstract

This document provides a description of optimization techniques for video encoders and receiving systems for machine consumption. It provides a concept-level overview of recent practices and references to technical articles that describe further details. It also provides comments on some technical aspects and identifies situations where cautions should be taken when interpreting the results.

# Scope

This document provides summary information about optimizations for encoders and receiving systems for conducting machine analysis tasks on coded video content using video coding standards developed in the ITU-T SG 16 Visual Coding Experts Group (VCEG) and ISO/IEC JTC 1/SC 29 Moving Picture Experts Group (MPEG) communities. This document does not represent an authoritative recommendation for how encoders and receiving systems should be optimized. It merely describes technologies that have recently been studied and demonstrated benefits to improvement on coding efficiency for machine tasks.

# Normative references

There are no normative references in this document.

# Terms and definitions

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

* ISO Online browsing platform: available at <https://www.iso.org/obp>
* IEC Electropedia: available at <http://www.electropedia.org/>

## Definitions

**Machine consumption**

A machine vision task such as object detection, instance segmentation or object tracking etc. being used on the decoded video.

## Abbreviations and acronyms

This Technical Report uses the following abbreviations and acronyms:

|  |  |
| --- | --- |
| AVC | Advanced Video Coding (Rec. ITU-T H.264 | ISO/IEC 14496-10) |
| BD-rate | Bjøntegaard Delta bit rate |
| CfE | Call for Evidence |
| CfP | Call for Proposals |
| CTU | Coding Tree Unit |
| HEVC | High Efficiency Video Coding (Rec. ITU-T H.265 | ISO/IEC 23008-2) |
| JVET | Joint Video Experts Team (for development of VVC) |
| mAP | Mean Average Precision |
| MOTA | Multiple Object Tracking Accuracy |
| MPEG | Moving Picture Experts Group |
| NNPF | Neural-Network Post-Filter |
| NNPFA | Neural-Network Post-Filter Activation |
| NNPFC | Neural-Network Post-Filter Characteristics |
| PSNR | Peak Signal-to-Noise Ratio |
| QP | Quantization Parameter |
| RoI | Region of Interest |
| SEI | Supplemental Enhancement Information |
| TID | Temporal Identifier |
| URI | Uniform Resource Identifier |
| VCEG | Video Coding Experts Group |
| VSEI | Versatile Supplemental Enhancement Information Messages for Coded Video Bitstreams (Rec. ITU-T H.274 | ISO/IEC 23002-7) |
| VVC | Versatile Video Coding (Rec. ITU-T H.266 | ISO/IEC 23090-3) |
| *Y′CBCR* | Colour space representation commonly used for video/image distribution, also written as *YUV* |
| *YUV* | Colour space representation commonly used for video/image distribution, also written as *Y′CBCR* |

# Overview

Similar to most video processing systems, there are four main processing steps, as shown in Figure 1. As the scope of this report focuses on optimizations for encoders and receiving systems, technologies for pre-processing, encoding and post-processing are described in this report. The decoding process, on the other hand, is fully specified in the respective Versatile Video Coding (VVC), High Efficiency Video Coding (HEVC) and Advanced Video Coding (AVC) video coding standards, amongst others, and a decoder must fully comply to the intended profile and level to properly decode and output the reconstructed video samples from a given input bitstream.

Input video

Pre-processing

Encoding

Decoding

Post-processing

Machine consumption

Figure 1. General processing pipeline

An overview of the commonly used practices for evaluating encoder optimization technologies for machine consumption in JVET and MPEG communities can be found in clause 5. A description of different pre-processing methods can be found in clause 6. Encoder optimizations and processes are detailed in clause 7 and post-processing methods are described in clause 8. Metadata that can be useful for machine consumption applications is described in clause 9.

## Background

In July 2019 the Requirements subgroup of ISO/IEC JTC 1/SC 29/WG 11 (MPEG) started exploration activities in the area of video coding for machines, with the initial goal of defining use cases, requirements and evaluation framework. This work, which was continued by ISO/IEC JTC 1/SC 29/WG 2, resulted in a formal call for evidence (CfE) in January 2021 [5]. As the responses to this CfE showed evidence of improvements over existing compression standards, a call for proposals (CfP) was issued in April 2022 [6].

Some responses to the CfP contained elements that can be used without modifications to existing video compression standards, and one response produced bit streams that were compliant to the VVC with pure encoder optimization [3]. As encoder optimization methods demonstrated significant compression benefits to machine consumption, compared with the anchor configuration that is setup for human consumption, JVET decided to conduct a study on optimization technologies for encoders and receiving systems for machine consumption. The outcome of this study is documented in this report.

## Use cases and applications

There are various use cases and applications using encoded video that benefit from optimizing both encoders and receiving systems for machine analysis. To give an overview some of them are listed below:

* Surveillance: To be able to handle the high number of sensors producing data, a large amount of bandwidth is needed. The number of sensors also has an impact on the computational load on the server side, as having to analyze the input from many sensors can become a large burden which can be eased by distributing the computation closer to the front-end devices.
* Intelligent transportation: A key aspect for vehicular applications is interoperability between not only vehicles from different vendors, but also the infrastructure of the current location. Connected vehicles are expected to play a significant role in the future of transport systems as they have the potential to increase safety, accessibility, and road usage efficiency. The high number of vehicles emphasizes the need of reducing the amount of data being transmitted to avoid overloading the network.
* Intelligent industry: One example in the area of intelligent industries is the visual analysis of materials and work pieces. In an automated industrial setting items can be analyzed to determine whether they fulfill certain requirements such as smoothness, evenness, or light reflection. If faults in work pieces are detected, they can be discarded or recycled.

# Evaluation methodology

A set of assessment metrics and measurement points are used for the evaluation of encoder optimization technologies for machine consumption. An overview evaluation framework is shown in Figure 2. Here the input video is encoded to generate a bit stream. This bit stream is then decoded, and the decoded video is used for the machine consumption task. Note that in this diagram the “Encoder” includes both pre-processing and encoding steps as in Figure 1, and the “Decoder” includes both decoding and post-processing steps shown in Figure 1.

Task performance calculation

Input video

Encoder

Decoder

Output video

bit rate

Ground truth

Machine consumption

YUV PSNR calculation

Figure 2. Measurement points used to evaluate technologies

The bit rate is determined based on the encoded bit stream and parameters of the input video such as frame rate and the number of total frames. The following equation can be applied:

(1)

Encoding for video distribution is ordinarily performed in the *Y′CBCR* domain (nicknamed *YUV* herein for brevity and ease of typing). For standard-dynamic range video, the distortion metric primarily used in the video coding standardization community has been the Peak Signal to Noise Ratio (PSNR). A detailed description on how to determine PSNR can for example be found in [2].

For different machine consumption tasks different metrics are used. For example, the performance for the object detection and instance segmentation tasks is usually measured in mean average precision (mAP). This metric indicates what percentage of objects are correctly identified by having sufficient overlap between the detected object and the ground truth as well as being assigned the correct object class. Then the share of correctly identified objects for each class is determined, and finally the score for each class is averaged. There are different variants of this metric:

* mAP@0.5: For an object to be counted as correctly identified the overlap between the detected bounding box and the bounding box in the ground truth needs to be at least 0.5. Sometimes this variant of the mAP metric is also referred to as mAP50.
* mAP@[0.5:0.05:0.95]: In this variant a total of ten mAP scores with increasing overlap thresholds are calculated. For each iteration the overlap threshold is increased by 0.05, starting at 0.5 and reaching all the way to 0.95. Once all ten scores are determined, the average of these scores is calculated to produce the final mAP performance.

(2)

For the object tracking task, performance is often measured in multiple object tracking accuracy (MOTA). This metrics takes several factors into account: (i) false positives, i.e., erroneously detected objects, (ii) false negatives, i.e., objects missed by the tracker, and (iii) mismatches, i.e., objects that were assigned a new identificatory when switching frames. The MOTA score can be calculated using equation (3), where *FPt* is the number of false positives in frame *t*, *FNt* the number of false negatives in frame *t*, *mmet* the number of mismatches in frame *t*, and *gt* the number of objects in frame *t*.

(3)

To compare the performance of a technology against the reference the well-known Bjøntegaard delta bit rate (BD-rate) metric is used, which was first introduced in [1]. Information on how BD-rate is calculated can be found in [2]. One major difference to [2] is that instead of PSNR as the distortion metric the appropriate machine task metric is used, i.e., for object detection and instance segmentation mAP, and for object tracking MOTA.

More details about the evaluation process for the study of optimizations for encoders and receiving systems for machine analysis used by JVET can be found in the related document on common test conditions [4].

# Pre-processing technologies

There are various technologies that can be applied to the input video. While some technologies alter the source, others do not change the pixel values and only extract information that the encoder later can use to improve the encoding performance.

## Region of Interest-based methods

One often-used optimization method is region of interest (RoI)-based coding. Here the input video is analyzed in some way and the result of this analysis is made available to the encoder, which in turn can optimize the encoding towards machine consumption. The analysis can be done using various methods, e.g., neural networks. An example of a pipeline that can be used for RoI-based approaches is shown in Figure 3.

Input video

Analysis

Encoder

Decoder

Machine consumption

Figure 3. Pipeline for RoI-based systems

In one implementation example, an object detection network is used to analyze the input data. This network produces a list of objects that can be found in the current picture. The information needed to describe each object includes the index of the picture in which the object can be found and the position of the object in the picture. Some networks might provide more information than this and the encoder might choose to select a subset of all objects by filtering based on for example the class of an object or the estimated likelihood of an object of the described class being at the described position. In a similar approach, a segmentation network can be used where the object is not described by a bounding box but by a segmentation mask indicating exactly which pixels belong to the object. The list produced during the analysis can then be used by the encoder, for example to separate foreground and background with the purpose of encoding the foreground at a better quality and the background at a lower quality. One such encoding method is described in clause 7.1. In this example, the analysis does not change the input video, which is forwarded without any changes to the encoder.

In other RoI-based methods, the pre-processing might change the input video, for example by applying different pre-processing methods on the foreground and background, or specific parts of the video, such as the background, may be subsampled.

In one implementation example, an object segmentation network is used to analyze the input data first. The network produces a list of objects segmented with the object shapes in the current picture. The object shapes and positions could be represented, for example, by segmentation masks. More information such as the object class or the estimated likelihood of the object segment could also be provided by the network to identify the objects. Based on the object information, spatial complexity and temporal complexity can be derived and then RoI-based pre-processing on the input video can be adapted based on the spatial and temporal complexity. The spatial complexity here indicates the averaged object size which can be calculated by dividing the percentage of the area covered by the objects by the total number of the objects. Temporal complexity indicates the content changes between two pictures which can be calculated by various methods, for example, by taking the mean absolute difference of the collocated pixels in two pictures..

## Pre-processing methods of foreground and background

After pre-analysis that determines the foreground and background areas, one straightforward way to handle the background that is less critical for machine consumption is to “eliminate” it by setting the corresponding sample values in the background to a constant value. However, some portions of background, for example those immediately surrounding the foreground area, could still be useful for machine vision tasks. Therefore, machine vision-related background regions can be preserved to a certain extent with low-pass filtering, such as a Gaussian filter with a sliding window, where the window size can be set based on the input video resolution.

Moreover, extracted features can reveal refined importance information of the input video. In other words, compared with binary classification of foreground vs. background, these extracted features can provide importance information at a finer granularity. Therefore, such extracted features can be used to determine how to process foreground and background differently. In one implementation example, a feature map is extracted by a feature extraction network and based on the feature map, the parameters of a Gaussian smooth filter are adapted and then the adaptive filtering is applied on the picture. As the background area and foreground area have different features and even within the background or foreground area, different regions may have different features, the Gaussian smooth filter can be controlled at a finer granularity, which finally results in a more detailed pre-processing.

## Temporal subsampling

In some use cases, for example when the frame rate is high, a way to reduce the bit rate without a strong negative impact on the machine consumption performance is to skip certain frames and encode the video at a lower frame rate. One example is to remove every other frame from the input video and encode the video at half frame rate. This can be done in a dynamic manner, for example by evaluating the motion between two or more frames and if there is only little motion, a frame can be removed. In some cases, if the receiving system requires a specific frame rate, a corresponding post-processing technology that up-samples to full frame rate needs to be applied.

## Spatial subsampling

If the analysis of a video shows that it contains primarily large objects, one way to increase the BD-rate performance can be to perform spatial subsampling on the input video. This will result in fewer pixels in subsampled frames to encode, and thus likely faster encoding and bit rate savings. The spatial subsampling can be applied adaptively, for example, based on the diversity characteristics of the visual content and the target bit rate. For example, depending on if the input video is captured by regular camera as natural scenes, or is captured by infrared sensor as thermal images, different spatial subsampling methods can be applied.

## De-noising filter

Under some circumstances, various types of noise can be present in the video content. A de-noising filter can be applied on these contents to reduce unnecessary increases in bit rate and to avoid machine analysis performance degradation by filtering out the undesirable noise from the video contents while preserving important information for machine analysis. Various types of de-noising filters can be applied according to the characteristics of the noise. The strength of the filter can be adjusted based on the noise, and the filter can adaptively be turned on and off for either an entire picture or sequence, or only a part thereof.

It should be noted that some existing de-noising filters such as bilateral or anisotropic diffusion filters can preserve local details during de-noising. For applications that depend on such local details, filtering entire pictures using the same strength should be carefully considered.

# Encoding technologies

Some technologies can directly influence how the encoder performs and changes the distribution of bits on either a picture-level or a sequence-level.

## Quantization Parameter adaption for Region of Interest coding

One method that is available in many video compression standards is adaptive quantization parameter (QP). Here the encoder can change the QP value on a sub-picture level, for example the coding tree unit (CTU) level, to optimize the encoding for the application. Due to this versatility, adaptive QP can be used in many different use cases to improve performance without any changes to the decoding process.

The decision on where to change the QP value and how much the QP value should be changed can be made by the encoder based on an analysis of the input video. Another option is to utilize the output of an external analyzer such as described in clause 6.1. In this case, the encoder receives information about the positions of objects in each frame to make a differentiation between foreground and background.

One option is to use the base QP value of the picture for areas that contain objects, i.e., foreground areas, and an increased the QP value for background areas, resulting in fewer bits being used to encode the background. As the background is not needed for a good machine consumption performance, this is a straight-forward way to reduce the bit rate. As an extension, it can also be beneficial to encode large objects with slightly higher QP values. As it is generally easier to detect larger objects, reducing the bit rate for large objects usually does not reduce the performance of the machine consumption task.

Utilizing the analysis, complexity can be traded against bitrate. If a light-weight neural network is used to perform the analysis, the encoder is recommended to take into account that not all relevant objects may be found and thus it could be detrimental to reduce the quality for the background too much as there might be objects that the initial analysis missed. These objects might still be important for the machine consumption task and if the background is encoded in sufficient quality, the machine consumption network has a chance of detecting objects in the background even if they are coded in lower quality than the foreground area.

If the encoding system has a lot of resources, it can employ a neural network of higher complexity for the analysis. With a better and more certain analysis, the bit rate for the background can be reduced more as there are likely fewer objects that have been missed in the initial analysis.

## Quantization step changes for temporal layers

Commonly used encoder configurations place different pictures on different temporal layers, i.e., assigning different temporal identifiers (TID). This has the purpose to create hierarchical structures that indicate from which previously coded pictures the encoder can create predictions for the current picture. One aspect of these hierarchical structures is that pictures cannot be referenced by other pictures on a higher temporal layer. By this way, not every decoded picture needs to be stored in the decoded picture buffer. Another aspect of the hierarchical structure is that pictures on higher temporal layers can be encoded with higher QP values, i.e., lower quality, as they will be not or more rarely used as references by other frames. An example of a hierarchical structure is shown in Figure 4. The display order is left-to-right, and the numbers specify the order of the coded pictures in the bitstream.

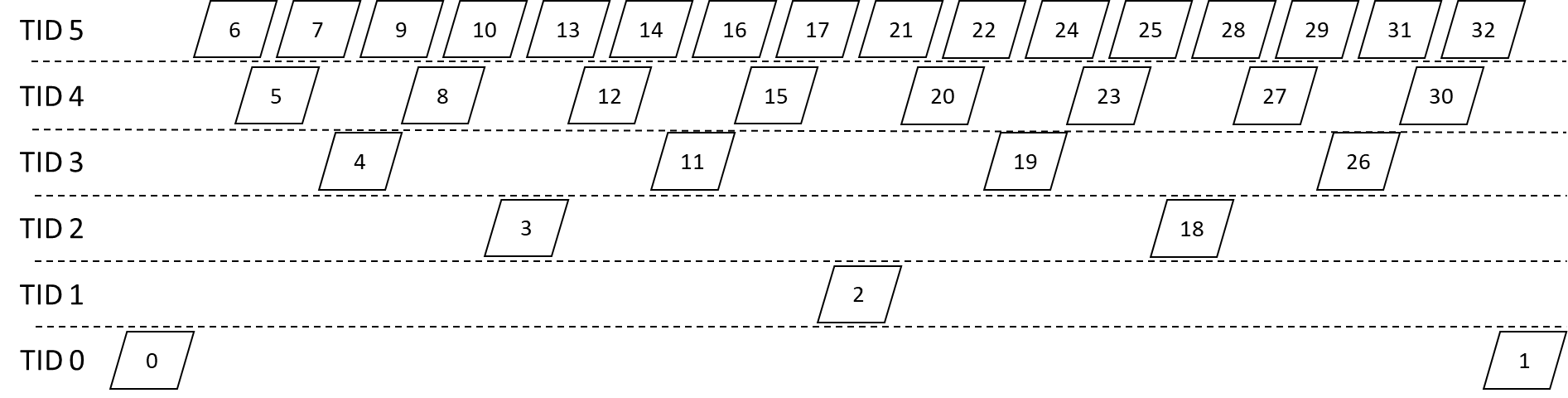


Figure 4. An example hierarchical referencing structure in a VVC random access bitstream

This hierarchy of frames can be exploited by encoding frames on higher temporal layers using higher QP values, i.e., reducing the number of bits spent on these frames in total. This is also done in the case of the common test conditions for standard definition range for VVC. In the use case of coding video content for machine consumption this characteristic can further be exploited by increasing the QP value for pictures on higher temporal layers more. Due to the motion compensation not many bits are needed to compress pictures on high temporal layers while those pictures are still able to be reconstructed with high quality.

# Post-processing technologies

There are various technologies that can be applied on the decoded video to make the post-processed video more suitable and better performing for machine consumption.

## Temporal resampling

Temporal resampling or frame interpolation can for example be performed using interpolation filters or neural networks specifically trained for this purpose.

## Spatial resampling

Spatial resampling can for example be performed using conventional filters (e.g., VVC interpolation filter, VVC reference picture resampling filter) or neural networks specifically trained for this purpose.

# Metadata

Metadata that is relevant to machine consumption may be transmitted with the coded bitstream to help the machine task performed on the decoded videos. There are various types of metadata that can aid a receiving system to optimize the decoded video. Supplemental Enhancement Information (SEI) messages specified by VSEI, HEVC or AVC can be an example.

## Annotated Regions SEI

The annotated regions SEI message specified in VSEI, HEVC and AVC can be used to signal parameters that identify annotated regions using bounding boxes representing the size and location of identified objects. Attributes about the annotated objects can also be optionally signaled, including a label for the object and the confidence level associated with the tracking and detection. This SEI message also contains a flag that can indicate whether a coded bitstream is not optimized for viewing by humans, i.e., it is encoded with machine consumption as the target, and a flag that can indicate if the motion information (motion vectors, modes) were selected in order to accurately track objection motion, rather than to optimize coding efficiency, i.e., with rate-distortion optimization. As object detection and tracking is computationally expensive, the annotated regions SEI message signaled with the coded bitstream allows the receiving systems to separate the objection detection or tracking functionality from the decoding of video.

## Neural-network post-filter SEI

The neural-network post-filter (NNPF) characteristics (NNPFC) SEI message and neural-network post-filter activation (NNPFA) SEI message are specified in version 3 of VSEI. These SEI messages can be used for the purpose of machine consumption.

The NNPFC SEI message describes the characteristics of a neural network that can be used to filter pictures after decoding and such filtering may be beneficial for machine analysis tasks. This SEI message may contain an indication of the purpose of the post-filter such as general visual quality improvement, chroma upsampling, resolution resampling, picture rate resampling, bit depth upsampling, or colorization. Note that the specific design of post-filters is not restricted by the SEI messages and post-filters that are suitable for the desired purposes may be used and described by this SEI message. The filter parameters of the neural network may be signaled in the NNPFC SEI message itself or could be identified by a uniform resource identifier (URI).

The NNPFA SEI message is used to enable or disable a post-filter specified by a referenced NNPFC SEI message on a particular picture.

Several different post-filters may be specified with multiple NNPFC SEI messages. In this case, the NNPFA SEI message can be used to indicate which of the available post-filters is to be applied to the current picture. By using several NNPFA SEI messages the usage of different post-filters on the same picture can be indicated.

1. Software implementation examples
   1. Example 1: Region of Interest-based adaptive QP

An implementation of the method described in this section can be found in the branch “JVET-AB0275” in a software repository containing implementation examples. This repository can be found at <https://vcgit.hhi.fraunhofer.de/jvet-ahg-ofm>.

This implementation consists of two main parts: the analyzer that is run before the encoder, and the modified VTM encoder.

* + 1. Analyzer

The analyzer is an object detection network that evaluates each frame to determine the positions of objects. In this implementation, the YOLOv3 network has been used for practicality reasons, but it is asserted that the same method can be applied using nearly any other object detection network. the output of the network is dumped into a file, which is then used as an additional input to the encoder.

* + 1. Encoder

The default VTM encoder has been extended with a new module to handle the generation of the adaptive QP map that indicates what offset to use for which CTU. In this module the information provided by the analyzer is evaluated and for each CTU the overlap with objects is determined. Based on the overlap, a CTU can be assigned to one of three possible categories:

* No overlap: if the CTU has no overlap with any objects, it is treated as a background CTU. This allows the encoder to increase the QP offset by a large value as there are no objects of interest in this CTU and thus no information gets lost by reducing the quality.
* Overlap only with large objects: objects are pre-sorted into large and small objects, which is determined by comparing the size of the area covered by the bounding box of the object to a pre-set threshold. If all objects the CTU overlaps with are large objects, the QP offset can be increased by an intermediate value as large objects are generally easy to detect and thus the detection does not suffer by reducing the quality slightly.
* Overlap with at least one small object: using the same sorting based on the size of the bound box as mentioned above, if a CTU has an overlap with at least one small object, the quality needs to be preserved as small objects are in many cases a significant challenge for machine analysis tasks. In this implementation the QP value is not increased for this category of CTUs.

Each category of CTUs corresponds to a value for the QP offset. This offset is then signaled using the delta QP mechanism that is part of the VVC standard.

* 1. Example 2: Pre-processing methods of foreground and background

An implementation of the method described in this section can be found in the branch “JVET-AD0047” in a software repository containing implementation examples. This repository can be found at <https://vcgit.hhi.fraunhofer.de/jvet-ahg-ofm>.

This implementation consists of two main parts: the pre-analysis and the pre-processing modules, as shown in Figure 5.

* + 1. Pre-analysis

The pre-analysis is an analysis module to extract the critical information of input pictures for machine vision. Specifically, in this implementation, an instance segmentation network is adopted to evaluate each input picture and generate the masks of instances. Then the instance masks are merged as a merged mask . Meanwhile, in order to achieve a fine-grained machine-oriented importance map, the feature maps in the instance segmentation network are extracted and fused (e.g., averaged and normalized) with those from all other channels to form an average feature map . The merge mask and the average feature map output by the pre-analysis module are sent to the following pre-processing module.

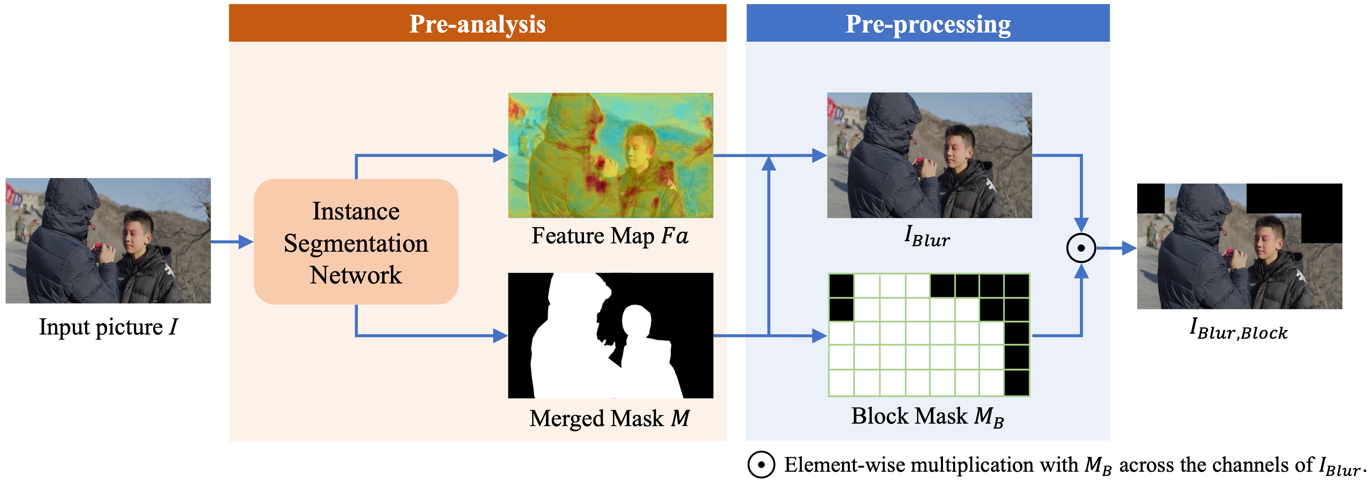


Figure 5 The framework of example implementation for the pre-processing method of foreground and background.

* + 1. Pre-processing

According to the merge mask and the average feature map , the pre-processing module further processes the input pictures. Blurring the background is an intuitive method to remove redundancy and maintain the machine vision performance. Herein, the blurred picture is obtained by blurring the background of the input picture sample by sample with a Gaussian filter, of which the standard deviation is set to the corresponding sample value in the average feature map . Moreover, a block mask is derived from , indicating the important regions to the machine vision. The representation compactness can be further improved by removing the unimportant regions, on the basis of . As such, the final result is formulated as , where indicates the element-wise multiplication with across the channels of .

For pre-processing of video data, a group of pictures can be processed using the same feature map and the same mask and in order to provide temporal stability.

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