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Analysis of Compressed Data Stream Content in HEVC Video Encoder

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***Abstract*—In this paper, a detailed analysis of the content of the bitstream, produced by the HEVC video encoder is presented. With the use of the HM 10.0 reference software the following statistics were investigated: 1) the amount of data in the encoded stream related to individual frame types, 2) the relationship between the value of the QP and the size of the bitstream at the output of the encoder, 3) contribution of individual types of data to I and B frames. The above mentioned aspects have been thoroughly explored for a wide range of target bitrates. The obtained results became the basis for highlighting guidelines that allow for efficient bitrate control in the HEVC encoder.**

***Keywords*—HEVC, video compression, compressed data stream analysis**

I. Introduction

A huge amount of data related to original video signal became an incentive to work out techniques of video compression. Over the years a number of video compression methods has been developed, many of them have been presented in the literature [1], [2]. Among the known solutions, the hybrid coding schemes are of particular importance, due to their high compression performance and consequently, many applications on the market [1], [2]. The state-of-the-art in the field of hybrid video compression is the new High Efficiency Video Coding (HEVC) technique [3], developed jointly by ISO/IEC MPEG and ITU-T VCEG experts, and standardized in 2013 [4]. Thanks to many improvements as well as new coding tools [3], HEVC offers up to 50% bitrate reduction in comparison to the AVC, while maintaining the same quality of encoded video [5]. For this reason, in the coming years, HEVC is envisaged to be the subject of industrial deployments in systems with high definition video signals.

The deployment of the new HEVC technology needs to be preceded by the works on efficient mechanisms of bitrate control e.g. [6]. Some of the known encoder control methods utilize the information about the content of the encoded data stream that is produced by the encoder [7]. The results of the analysis of data stream produced by the encoders of older generations (e.g. MPEG-2, AVC) are available in [8]. In the HEVC, the content of the encoded data stream is different, when compared to MPEG-2 or AVC (due to the new solutions in the structure of the encoder). First of all, HEVC encoder produces different syntax elements. The quantitative features of the stream (percentage distribution of individual types of data in the stream) are also different. As a result, research on the content of the encoded data stream must be repeated in order to work out the new encoder control solutions, dedicated to the HEVC technique. Thorough analysis of the HEVC bitstream content, and its properties, make the topic of the paper. In particular, the aim of this work is the analysis of such a HEVC data stream, which is the result of the encoder mode selection mechanism that ensures high efficiency video coding (see methodology of experiments). In this encoding scenario, the relationship between the bitrate and the quality of decoded pictures has already been the subject of thorough study on HEVC [5]. For this reason, the quality of the decoded pictures was not a subject of research in this paper.

The rest of the paper is organized as follows. In Section II detailed goals of the work have been presented. Section III reveals what experiments have been carried out and what was the methodology of these studies. Section IV presents experimental results together with comments and general conclusions. And the last, Section V summarizes the paper.

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II. Research Problem and Goal of the Work

Detailed knowledge about the content of the encoded video data stream is the basis for efficient control of bitrate in the encoder. Such knowledge will allow for more efficient distribution of the bit budget between individual frames of a video sequence. Although, some studies have been performed in this area earlier, they present preliminary results only. For example, separate and detailed results for I and B frames have not been presented in the literature so far (only averaged results were presented in [9]). The analysis has been performed for a specific (and narrow) range of quantization parameter (QP) values. Or, the results were averaged without presenting detailed values for individual syntax elements, that have been defined in HEVC [10]. The detailed analysis of the HEVC data stream content, performed for different scenarios of video encoding is the goal of this paper. Preliminary research has already been done by the authors and published in [11]. In this paper the continuation of the cited work is presented together with new results which are supplementary to the data already published in [11]. In particular, the following problems are explored in this paper:

1) What is the portion of the total bitstream used to encode I frames? What is that portion for B frames?
2) What amount of the encoded data stream is related to individual frame types?

3) What is the share of individual categories of syntax elements (residual data, motion data, control data) in encoded data stream? How does the value of bitrate affect the results?
4) What are the statistics of syntax elements in frames of a given type (I and B frames)?
5) What portion of image area can be encoded without the need of transmitting residual data for transform coefficients?

III. Methodology of the Research

In order to perform a thorough analysis of the HEVC encoded data stream and draw reliable conclusions, extensive experiments have been done. In particular, in experiments the commonly available HM 10.0 reference software of the HEVC [12] working under Common Test Condition (CTC) [13] has been used. CTC defines a set of conditions and encoder configurations designed as a common ground for the evaluation of HEVC related technology. Using this software, a series of experiments was done with the following encoding conditions:

- Seven 1920x1080@30Hz test video sequences were used (Fig. 1): *bluesky*, *pedestrianarea*, *riverbed*, *rushhour*, *station2*, *sunflower*, *tractor*. The sequences are recommended by ISO/IEC MPEG as well as ITU-T VCEG working groups as appropriate for the purposes of research works on video compression.
- Random access encoding scenario was used, as defined in CTC [13]. In particular, a video sequence was divided into Groups Of Pictures (GOP), with a strict division of a GOP into I-, B-frame types and hierarchical encoding of B-frame types (the so-called B_0, B_1, B_2 and B_3 frames). The higher value of subscript of B frame the lowest level in the hierarchical structure (see Fig. 2 for details).
- Experiments were carried out for a wide range of target bitrates (controlled by the quantization parameter QP in encoder). Tests were done for QP values from 10 to 40 with step equal to 1.
- Other settings of the encoder were set as suggested in CTC. Essential configuration parameters used for HEVC are presented in Table I.

TABLE I
Essential Configuration Parameters Used for HEVC Encoder

Parameter	Parameter Value
Profile	Main
GOP structure	$IB_3B_2B_3B_1B_3B_2B_3B_0$ ...
GOP size	8
Intra period	32
Hierarchical GOP	Yes
Number of referenced frames	4
Rate-distortion optimization	On
Search range for motion estimation	±64

As a result, 280 encoded data streams were achieved. Each of compressed video bitstream has been examined by using the Bitstream Analyzer software. The analyzer has been written in order to perform precise analysis of bitstream components. The analyzer entropy decodes the input bitstream and simulates the encoding process in order to calculate the number of bits per syntax element. The bits calculation is performed by the use of the CABAC counter precise estimator [14] instead of CABAC arithmetic encoder core. The CABAC counter allows for precise calculation of bits per syntax element (2^{-15} precision) and allows to avoid the arithmetic encoder flushing issue.

Fig. 1. Test video sequences used in experiments in order from top-left: *Bluesky*, *Pedestrianarea*, *Riverbed*, *Rushhour*, *Station2*, *Sunflower* and *Tractor*.

All results have been calculated for each of QP point with constant QP encoded bitstream and interpolated to common bitrate values.

The list of analyzed syntax elements in each syntax element category includes:

- ControlData:
  - *split_cu_flag,*
  - *cu_skip_flag,*
  - *pred_mode_flag,*
  - *part_mode,*
- IntraPred:
  - *prev_intra_luma_pred_flag,*
  - *mpm_idx,*
  - *rem_intra_luma_pred_mode,*
  - *intra_chroma_pred_mode,*
- MotionData:
  - *merge_idx,*
  - *merge_flag,*
  - *inter_pred_idc,*
  - *ref_idx_l0,*
  - *mvp_l0_flag,*
  - *ref_idx_l1,*
  - *mvp_l1_flag,*
  - *abs_mvd_greater0_flag,*
  - *abs_mvd_greater1_flag,*
  - *abs_mvd_minus2,*
  - *mvd_sign_flag,*
- ResidualData:
  - *rqt_root_cbf,*
  - *split_transform_flag,*

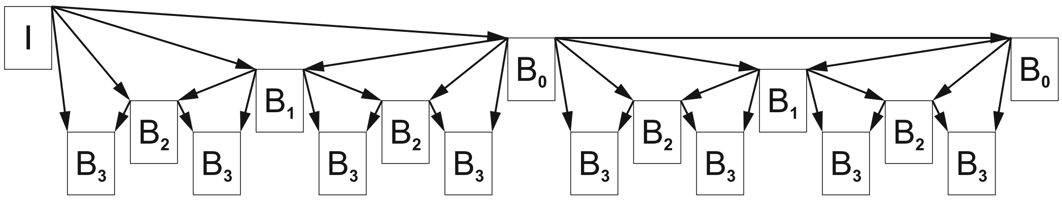


Fig. 2. Hierarchical coding scheme. For the sake of simplicity, only part of prediction directions are marked.

  - *cbf_cb,*
  - *cbf_cr,*
  - *cbf_luma,*
  - *transform_skip_flag,*
  - *last_sig_coeff_x_prefix,*
  - *last_sig_coeff_y_prefix,*
  - *last_sig_coeff_x_suffix,*
  - *last_sig_coeff_y_suffix,*
  - *coded_sub_block_flag,*
  - *sig_coeff_flag,*
  - *coeff_abs_level_greater1_flag,*
  - *coeff_abs_level_greater2_flag,*
  - *coeff_sign_flag,*
  - *coeff_abs_level_remaining,*
- Other:
  - *end_of_slice_segment_flag,*
  - *sao_merge_left_flag,*
  - *sao_merge_up_flag,*
  - *sao_type_idx_luma,*
  - *sao_type_idx_chroma,*
  - *sao_offset_abs,*
  - *sao_offset_sign,*
  - *sao_band_position,*
  - *sao_eo_class_luma,*
  - *sao_eo_class_chroma,*

Further in the paper, the numbers of bits that correspond to the above mentioned syntax element categories in pictures of individual types, i.e. I, B_0, B_1, B_2 and B_3 are studied.

IV. Experimental Results

In the encoder, the bitrate control mechanism relies on the adjustment of the quantization step size. In the HEVC encoder the choice is made at frame, slice and Coding Unit (CU) levels [3]. Quantization step size is determined in the HEVC by defining the value of quantization parameter (QP). The current value of QP is sent in the encoded data stream. This parameter influences quantization of transform coefficients and thus has a direct impact on the bitrate of encoded data stream that is produced by the encoder. Therefore, the relationship between the value of QP and the bitrate of the encoded data stream has been studied in the first phase of the experiment.

A. Bitrate vs. Quantization Parameter

The results shown in Fig. 3 present the relationship between the value of QP and the bitrate for a set of test video sequences. As can be seen it depends significantly on the content of a video sequence. Thus, the analysis of the complexity of image content is an essential step of the algorithm that determines the value of QP for a given bitrate.

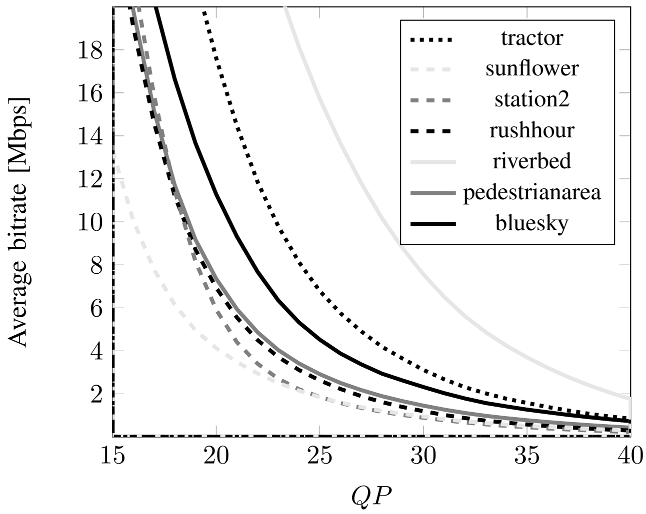


Fig. 3. Experimental curves for all test sequences. Relationship between QP and bitrate.

B. Contribution of Individual Frame Types

In practice, the Group of Pictures (GOP) structure contains both the I and B types of frames. Therefore, there is a need for bitrate allocation inside the GOP between images of different types. During the experiments, the structure of GOP that is recommended by JCT-VC (Joint Collaborative Team on Video Coding of ITU-T SG16 WP3 and ISO/IEC JTC1/SC29/WG11) experts group as appropriate for encoding scenarios with high compression performance [13] has been used. The distribution of bits between the images of different types for assumed GOP structure is shown in Fig. 4, 5, 6 and 7.

For the commonly used QP values in the range of 15–40, the results can be summarized as following.

Although there is only one I frame in the GOP (the whole GOP contains 32 frames), on average even 10–30% bits are devoted to encode this frame of type I (see Fig. 4 and 5). Such a high percentage of bits for the I frames is a result of a much lower efficiency of intra-frame encoding as compared to inter-frame compression in the case of B frames. The averaged results revealed that, the contribution of the bits required by I frames ($bits_I$) to the total number of bits representing entire sequence ($bits_{total}$) can be modeled as:

$$\frac{bits_I}{bits_{total}} \approx 0.0073 \cdot QP + 0.0141 \tag{1}$$

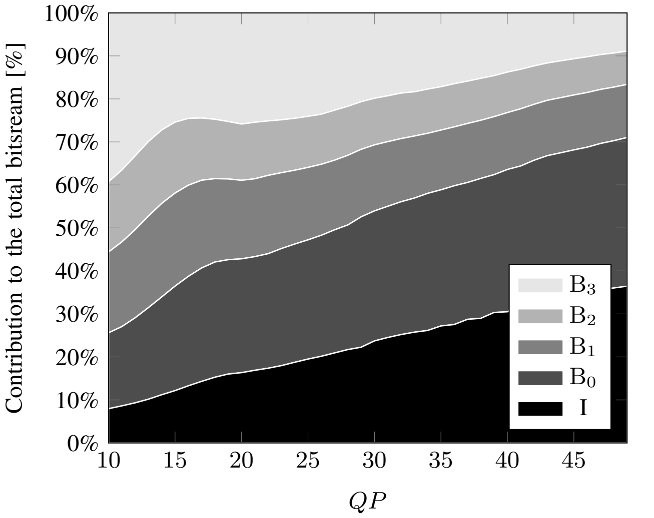


Fig. 4. Contributions of individual frame types to the total bitstream, averaged over 7 test sequences in relation to QP value.

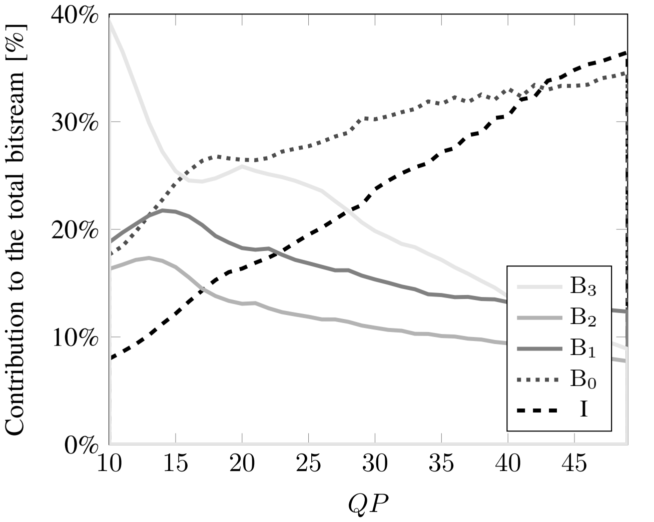


Fig. 5. Contributions of individual frame types to the total bitstream, averaged over 7 test sequences in relation to QP value.

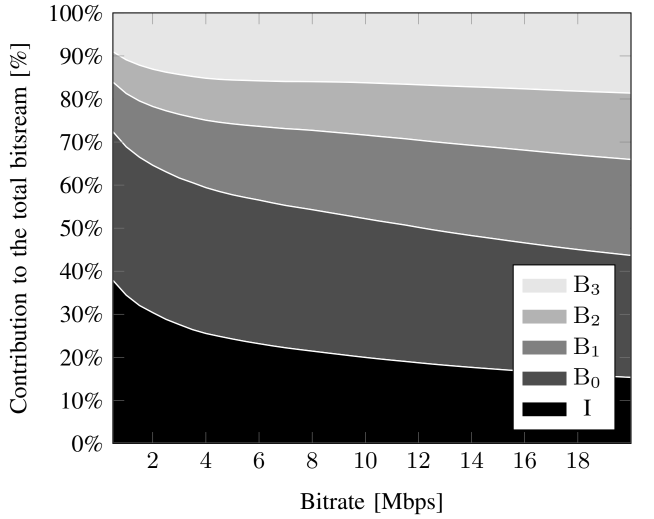


Fig. 6. Contributions of individual frame types to the total bitrate, averaged over 7 test sequences in relation to sequence bitrate.

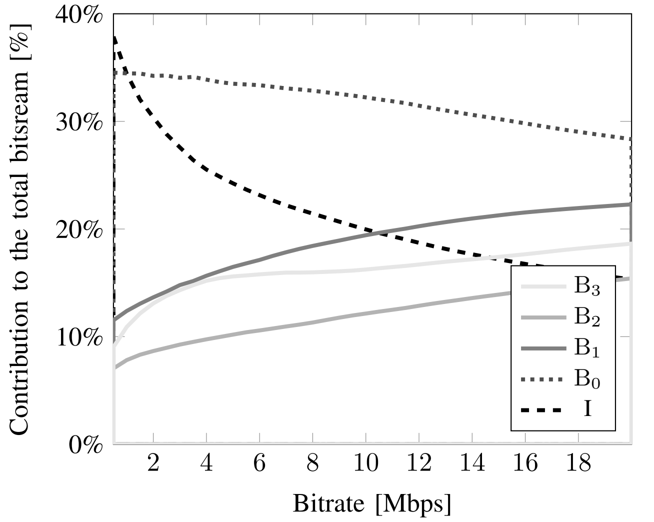


Fig. 7. Contributions of individual frame types to the total bitrate, averaged over 7 test sequences in relation to sequence bitrate.

with the coefficient of determination (in statistical programs often marked as R^2) [15] equal to 0.9973. Such high value of coefficient of determination means that this approximation is almost perfect.

For B_0 frame types (the highest level of B frames in the hierarchical structure of GOP), the comparable number of bits as for I frames is used: 15–40% of the total bitstream. In this way, the I and B_0 frame types constitute 60–70% of the encoded data stream (for the lowest tested QP it is about 25%).

The rest of bitstream conveys data for B_1, B_2 and B_3 frames, specifically: 20% for B_1 frames, about 15% for B_2 frames, and depending on the value of QP, between 10–40% for B_3 frames.

The presented quantitative results of the research can be the basis of the proper allocation of the bits budget between the individual images in the GOP. In order to increase the efficiency of the bitrate control algorithm, the nature of image content (image complexity) should additionally be taken into account when distributing bits among images.

From the point of view of bit allocation between images, it is more desirable to know distribution of bits between images, but not in the function of QP, but in the function of bitrate of encoded data instead. The results of the study, which was carried out for a wide range of bitrates (500 kbps to 20 Mbps) are shown in Fig. 6 and 7. As can be seen, reducing the bitrate results in monotonic increase of the amount of data associated with I and B_0 frames. It is obvious that smaller bitrates correspond to stronger quantization of residual data. Due to the fact, that the prediction of image samples works more efficiently in the case of B_1, B_2 and B_3 frames (when compared to I and B_0 frames), a stronger quantization reduces more data in B_1, B_2 and B_3 frames than in other types of images. It has been experimentally confirmed in our additional study described in Section IV-D.

For applications in high-quality digital television (including Full HD images) and the HEVC technology, the useful range of bitrates is 4–5 Mbps. In this particular application, the I frames constitute about 25% of the total bitstream, B_0 frames 34%, B_1 frames about 16%, B_2 frames 10%, and B_3 frames 15% of the total bitstream.

When presenting the results of Fig. 6 in the form as in Fig. 7 it is possible to propose mathematical models, that allow approximation of the share of individual types of frames in encoded data stream (as a function of bitrate). On average, the number of bits required by individual types of frames ($bits_{type-of-frame}$) to the total number of bits representing entire sequence ($bits_{total}$) in relation to bitrate in Mbps can be approximated as follows:

1) Data for I frames may be approximated by function:
$$\frac{bits_I}{bits_{total}} \approx -0.0438 \cdot log_2(Bitrate) + 0.3437 \quad (2)$$
with the coefficient of determination equal to 0.9988. Such high value of coefficient of determination means that this approximation is almost perfect.
2) In the case of B_0 frames the linear function is sufficient:
$$\frac{bits_{B_0}}{bits_{total}} \approx -0.0033 \cdot Bitrate + 0.0352 \quad (3)$$
with the coefficient of determination equal to 0.9862.
3) For B_1 frames, high accuracy of approximation is provided by power function:
$$\frac{bits_{B_1}}{bits_{total}} \approx 0.1214 \cdot Bitrate^{0.2028} \quad (4)$$
with the coefficient of determination equal to 0.9875.
4) In the case of B_2 frames data may be approximated by the linear function:
$$\frac{bits_{B_2}}{bits_{total}} \approx 0.0037 \cdot Bitrate + 0.0825 \quad (5)$$
with the coefficient of determination equal to 0.994.
5) In the case of B_3 frames data may be approximated by the linear function:
$$\frac{bits_{B_3}}{bits_{total}} \approx 0.0159 \cdot log_2(Bitrate) + 0.1134 \quad (6)$$
with the coefficient of determination equal to 0.97.

Adjustment of the coefficients values of the above mentioned functions is beyond the scope of this work and should be the subject of further research.

C. Contribution of Categories of Syntax Elements

On the basis of detailed results that were collected during the experiments (distribution of individual syntax elements in encoded data stream - see methodology of experiments), the data that present distribution of five syntax element categories were prepared:

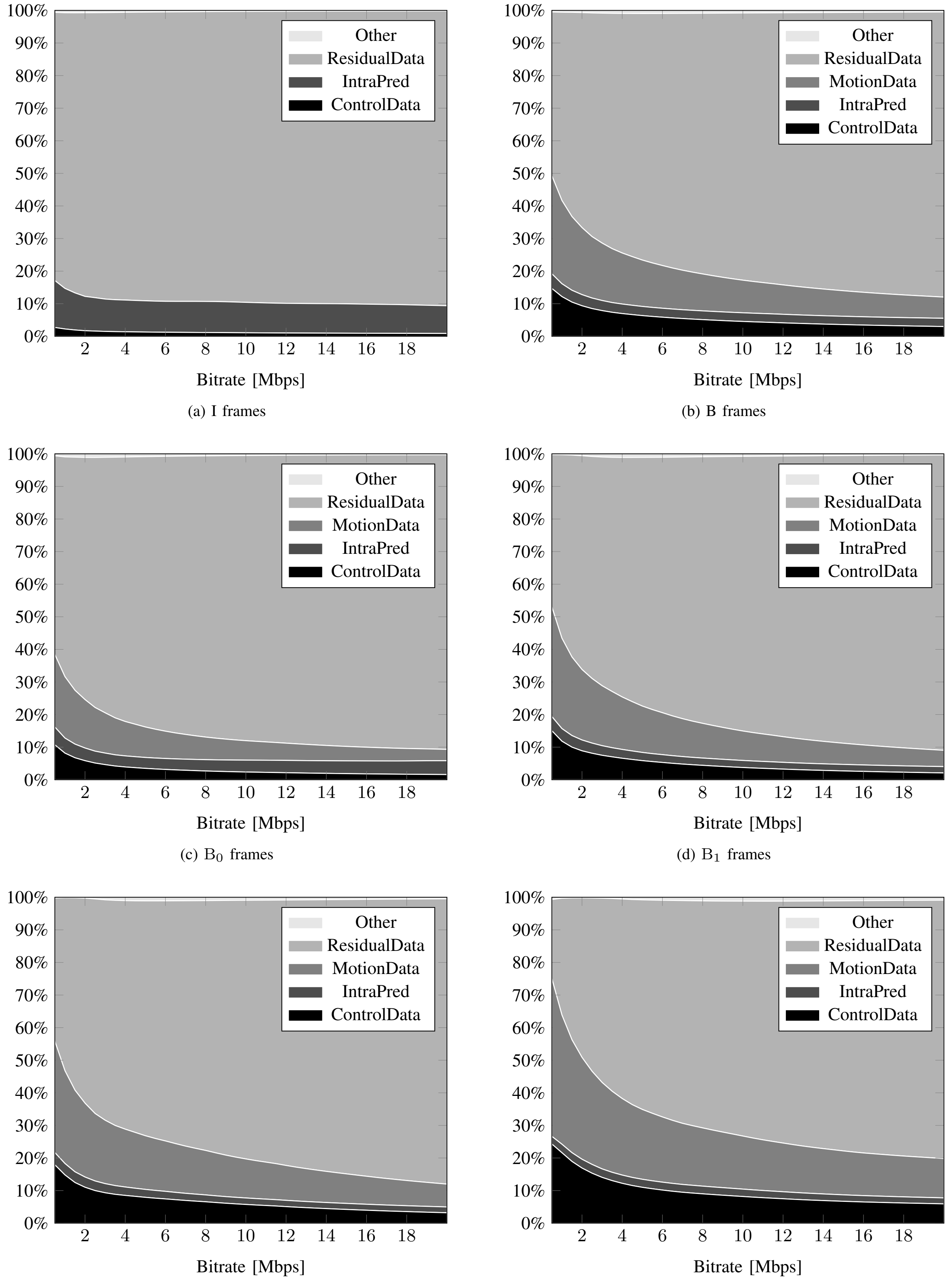
1) residual data of picture samples (ResidualData),
2) motion data (MotionData),
3) control data (ControlData),
4) information about intra prediction mode (IntraPred),
5) other types of data (Other).

Detailed statistics of these categories of syntax elements are different in individual types of frames - Fig. 8. In the case of I frames, there is no motion data (see Fig. 8a). It results in a greater share of data related to residual data of picture samples - which is 85–90% of the total bitstream. The remainder of the stream is intra prediction signalization and control data. There is a small variability of the results in function of bitrate. The value of bitrate affects the bitstream content of B frames to a greater extent (see Fig. 8b). In the case of residual data, they constitute 50–80% of the bitstream, for the low and high bitrates respectively. The motion data takes up 10–30% of bitstream, with larger share for smaller bitrates. The remaining types of data make 5–15% of the bitstream. The detailed results for individual types of B frames are presented in Fig. 8c, 8d, 8e and 8f. As can be seen, the results for B_1 and B_2 types of frames are very similar, but different than those obtained for B_0 and B_3 frames. Smaller contribution of residual data for the lower bitrates, and thereby higher share of other types of data in this scenario is a direct result of a stronger quantization of residual data.

It should be noted that the size of the HEVC data stream is twice lower than that at the output of the AVC encoder. However, due to the use of more efficient techniques of image prediction and motion data coding, the proportions of individual types of data in encoded stream of data have not substantially changed. Residual data of image prediction is still an essential part of the encoded data stream. Therefore, the selection of QP value in the HEVC encoder will be the basic tool of the bitrate control, similarly as in the case of the older video compression techniques e.g. [16], [17] for MPEG-2 and [18], [19] for AVC.

D. Quantized Transform Coefficients

As mentioned before, the prediction of image samples works more efficiently in the case of B_1, B_2 and B_3 frames. Moreover, a stronger quantization reduces more data in B_1, B_2 and B_3 frames than in other types of frames. In order to confirm this, additional study has been performed. The percentage of image blocks with no residual signal of image samples prediction was measured for I, B_0, B_1, B_2 and B_3 frames (see Fig. 9). Due to limited efficiency of intra-frame prediction, for only 3% of image area, there are no non-zero transform coefficients of prediction error samples. Moreover, this percentage is quite independent from the value of bitrate. Much higher efficiency of predictive coding has been observed in B frames. For broadcast applications a useful range of bitrates (4–5 Mbps for HD resolution, 30 fps), for B_0 frames, the percentage of the image area in which no prediction error of image samples is transmitted is about 17%. In the case of B_1 frames it is about 47%. In the case of B_2 and B_3 frames, 61% and 79% respectively. While the bitrate increases, the above mentioned values decrease. The experimental results indicate a very high efficiency of inter-frame prediction in the HEVC.



(a) I frames

(b) B frames

(c) B_0 frames

(d) B_1 frames

(e) B_2 frames

(f) B_3 frames

Fig. 8. Contributions of categories of syntax elements.

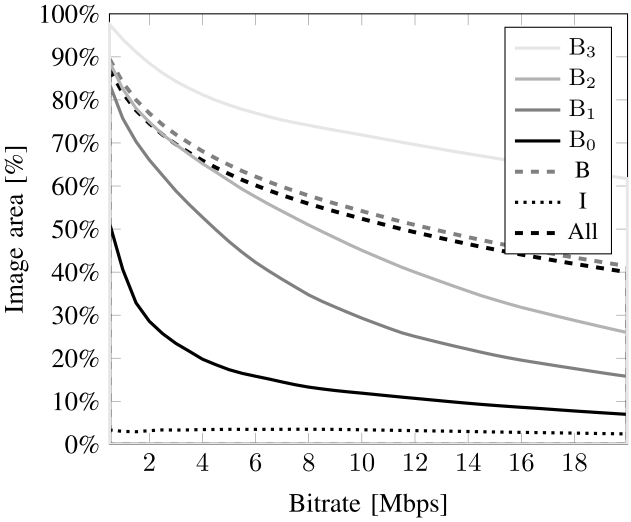


Fig. 9. Percentage of image area where no residual data (no transform coefficients) have been transmitted.

V. Conclusions and Final Remarks

The paper documents the results of research that was conducted in order to analyze the compressed data stream from the HEVC video encoder. The analysis was focused on the extraction of the data that will be useful in the development of the mechanisms for HEVC bitrate control. Detailed results were presented and discussed in section IV.

On the basis of the obtained results, the following general conclusions can be highlighted:

1) As expected, the contribution of individual frame types in the stream of the encoded data is not the same. The exact share of data strictly depends on bitrate and the type of frame (refer to Fig. 6 and 7). Depending on the type of frame, data can be modeled by linear, logarithmic or power functions (equations 2–6 in Section IV).
2) The relationship between QP and the target bitrate strongly depends on the type of a video. Although this relation may be modeled by a forth order polynomial function, the analysis of the image content is necessary to calculate the parameters of the function.
3) Although the prediction mechanisms in HEVC are much better than the ones from the previous standards, there is still a large percentage of data related to the prediction error of image samples present in the HEVC encoded bitstream. In the case of I frames it is 85–90% of all data, whilst in B frames it is 50–80%. Therefore, similarly as in older standards (e.g. AVC) the bitrate control can be done on the basis of the amount of data that represents the residual signal.
4) The highly improved compression efficiency of HEVC is related to very efficient prediction of image samples, in particular inter-frame prediction. For broadcast quality video, on average, for about 70% of picture blocks, no prediction error is transmitted.

Presented results make the basis for further works of authors that concern the bitrate control of the HEVC encoder. The works are carried out under the LIDER Grant of the National Center for Research and Development, Poland.

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