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RESEARCH ARTICLE

Analysis of the Limitations of Further Improvement of the Efficiency of VVC-CABAC

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ABSTRACT Hybrid video compression plays an invaluable role in digital video transmission and storage services and systems. It performs several-hundred-fold reduction in the amount of video data, which makes these systems much more efficient. An important element of hybrid video compression is entropy coding of the data. The state-of-the-art in this field is the newest variant of the Context-based Adaptive Binary Arithmetic Coding entropy compression algorithm which recently became part of the new Versatile Video Coding technology. This work is a part of research that is currently underway to further improve the Context-based Adaptive Binary Arithmetic Coding technique. This paper provides analysis of the potential for further improvement of the Context-based Adaptive Binary Arithmetic Coding technique by more accurate calculation of probabilities of data symbols. The mentioned technique calculates those probabilities by the use of idea of the two-parameters hypothesis. For the needs of analysis presented in this paper, an extension of the aforementioned idea was proposed which consists of three- and four-parameters hypothesis. In addition, the paper shows the importance of proper calibration of parameter values of the method on efficiency of data compression. Results of experiments show that for the considered in the paper variants of the algorithm improvement the possible efficiency gain is at levels 0.11% and 0.167%, for the three- and four-parameter hypothesis, respectively.

INDEX TERMS Probability estimation, entropy coding, arithmetic coding, VVC-CABAC, video compression.

I. INTRODUCTION

More than 80% of all data that is currently transmitted in ICT networks is data representing digital video [1]. Video streaming services (e.g., Netflix), platforms for the exchange of videos between users (e.g., WhatsApp, TikTok), and finally, television on IP networks are only some examples of multimedia systems in which huge amounts of video data are sent. Due to the increasing popularity of these systems, it should be expected that the percentage of video data mentioned above will increase even more in the coming years.

To meet the difficult challenge of digital video transmission, the data must be compressed beforehand. This operation uses a wide range of specially designed video processing and encoding algorithms that aim at reduction the number of bits describing the video content (while ensuring high quality of video content after decompression). The aforementioned reduction of the set of bits is therefore the basis for efficient operation of modern multimedia systems.

As far as video compression is concerned, the techniques of hybrid coding of a video have gained the greatest practical significance [2], [3], [4], [5], [6], [7], [8], [9], [10]. They have been included in many international recommendations and technologies developed in businesses [2], [4], [5], [8], [10]. In order to represent efficiently content of each video frame, hybrid coding determines data of syntax elements specially designed for this purpose. They inform about the motion occurring in a video and its parameters, the results of

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predicting the content of video frames, and the compression methods used for a given parts of video frames.

An inherent element of hybrid compression is the entropy coding of syntax elements data. This encoding is completely lossless. Nevertheless, by reducing the statistical redundancy that is observed within this data, entropy coding significantly improves results of video compression [11]. Hence, the importance of this coding for the task of efficient compression of a video. Entropy coding is the subject of interest of this work.

The Context-based Adaptive Binary Arithmetic Coding (CABAC) technique, developed after year 2000, represents the state-of-the-art of entropy compression of video data [12]. This technique implements very advanced mechanisms of arithmetic coding [13], [14], [15], [16], [17], [18], [19], [20], combined with proper pre-processing of syntax elements data. From the point of view of data compression efficiency, the CABAC technique outclasses other entropy coding methods that have been proposed in the context of video data compression [12]. Hence, the application of the CABAC technique in the latest generation of hybrid video encoders AVC (MPEG-4 Part 10 or H.264 [3], [4], HEVC (MPEG-H Part 2 or H.265) [7], [8], VVC (MPEG-I Part 3 or H.266) [9], [10]).

Therefore, the CABAC technique has been the starting point in most of the advanced research that has been carried out in the field in recent years. This methodology has also become the basis of this work. The goal was to develop further improvements to the CABAC technique resulting in increased coding efficiency of video data. The most recent outcome of these efforts is the latest version of the CABAC technique [21] (called later as VVC-CABAC), which has become part of the newest generation of video encoding – VVC – developed at the end of 2020 [9], [10]. The introduced improvements (relative to the earlier version of the CABAC algorithm, known from HEVC video encoding [7], [8]), allowed a further reduction of the video data bitrate by almost 0.8%, which, in the domain of lossless coding, is a really remarkable result. The possibilities of further improving this latest version of the CABAC technique are currently being explored in the world.

This work is a part of such research. Its focus is to assess the potential to further improve the performance of the VVC-CABAC technique. In particular, the authors' research presented in the paper focuses on the ideas of more accurate estimation of the probabilities of encoded data symbols, which is an important procedure of the CABAC technique. Due to the use of this technique in video encoders and the huge share of video data in the global telecommunications traffic, improving the compression efficiency of the method by even a fraction of a percent will be associated with significant bit savings on a global scale.

II. RATIONALE AND LITERATURE REVIEW

A. KEY ELEMENTS OF THE CABAC TECHNIQUE FROM PERSPECTIVE OF THE PRESENTED RESEARCH

The CABAC technique performs an advanced compression of syntax elements data [12]. Within this technique, three separate stages of data processing should be indicated, the efficiency of which translates into the final performance of entropy coding. These are: binarization of syntax elements, creating the sub-streams of binary symbols (called bins) and estimation of probabilities of bins within sub-streams (context modelling), and arithmetic encoding of bins (see Fig. 1.).

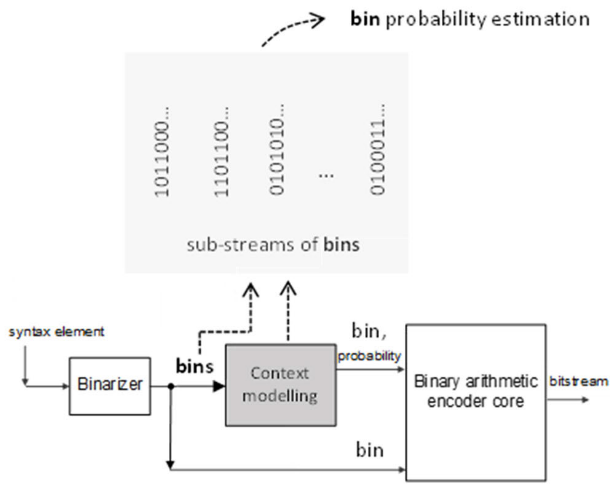

FIGURE 1. Main functional blocks in the CABAC technique.

The necessity to binarize syntax elements (which is realized in practice with dedicated variable-length codes) results from the use of binary arithmetic encoding in the CABAC technique (i.e., encoding of binary symbols (bins) with the value of 0 or 1). However, the subject of interest of this work is the second block of CABAC encoding – context modelling. In this part of the technique, two mechanisms are very important: 1) dividing the stream of bins into a large number of separate sub-streams, 2) the method of estimating the probabilities of bins in individual sub-streams. The last issue – bins probability estimation – is at the center of this paper.

The data of syntax elements represents different types of information (as mentioned earlier) and, therefore, exhibit different statistical properties. Within the binarized word of the syntax element, the statistics of individual bins may be also different. Thus, an important step in CABAC encoding is to divide the stream of bins into a large number of independent bins' sub-streams. The goal of this step is to properly group those bins that show similar statistical characteristics. Here, the CABAC algorithm uses very advanced solutions, which take into account factors like the type of the coded syntax element, the position of the bin in the binarized word, or values of the data that, within a video frame, are neighboring to the currently encoded data [12]. The independent estimation of probabilities of bins in the sub-streams significantly improves the data coding efficiency. The knowledge of the probabilities of bins is the basis for their efficient representation in an arithmetic encoder.

B. ESTIMATION OF PROBABILITIES OF BINS

As indicated above the efficiency of data encoding is strongly influenced by the same algorithm of bin probability estimation that is realized within sub-streams. Initially, in the earlier versions of the CABAC technique (those that were used in the AVC and HEVC video encoders) [12], [22], the "exponential aging" model of data statistics [15] was used. According to this model, the probability of occurrence of the coded bin depends on the sequence of bins that precedes it in the sub-stream, and the influence of the individual bins of this sequence is not the same here. The influence of the last bins of the sequence (which immediately precede the currently encoded bin) is much bigger than that of bins that appeared much earlier. In line with this concept, the first versions of the CABAC algorithm took into account $N = 19.69$ "past" bins in the procedure of determining the statistics for the currently encoded bin [12], [22]. In the case of a bin referred to as *LPS* (least probable symbol), the bin probability was defined as:

$$p_{new}\left(LPS\right) = \alpha \cdot y\left(bin\right) + \left(1-\alpha\right) \cdot p_{old}\left(LPS\right) \quad (1)$$

where:

$p_{new}\left(LPS\right)$	is the estimated probability of the *LPS* bin,
$p_{old}\left(LPS\right)$	is the probability of the *LPS* bin calculated earlier,
$y\left(bin\right)$	is equal to 0 if the current bin is an *MPS* symbol, and equal to 1 otherwise,
α	parameter directly depends on N and is equal to: $\alpha = 1/N$.

As one can see, procedure of probabilities estimation is controlled by α, the value of which depends precisely on the number N of previously encoded bins. In the adopted model of "exponential aging" it also determines the "strength" of the influence of previously encoded bins on the change of probability of the current bin.

The latest improvement of the original CABAC solution is a further extension of the above concept by using a model with two different parameters α. The basis for such an extension is the research, the results of which are presented in [23] and [24]. Referring to the formula (1), the proposals in [23] and [24] calculate two different probability values, using two separate α parameters with the values: $\alpha_1 = 1/16$ and $\alpha_2 = 1/256$. The parameter values were adopted in such a way as to take into account two different scenarios during the bin statistics estimation: quick adaptation of the probability values as a response to changing values of coded bins (parameter α_1), and slow adaptation (parameter α_2). As it is generally not known *a priori* which of these scenarios will turn out to be more advantageous (while coding the current bin), the method finally does simple averaging of both obtained probabilities (see formula 2), thus obtaining the final result of bin statistics estimation.

$$p\left(bin\right) = 0.5 \cdot p_{\alpha_1} + 0.5 \cdot p_{\alpha_2} \quad (2)$$

As the experimental results show, the presented improvement gains the coding efficiency of CABAC by 0.5% - 0.8%, in terms of compression of syntax elements, which are present in the HEVC video encoder [23].

The last addition to the above improvement is the use of separate, dedicated values of α_1 and α_2 in individual sub-streams of bins [21]. This solution is part of the latest version of CABAC technique (hereinafter referred to as VVC-CABAC), incorporated into the new VVC standard of video encoding. In practice, each of the bins sub-streams uses its individual value α_1 which comes from the set {1/4, 1/8, 1/16, 1/32} and value α_2 that comes from the set {1/32, 1/64, 1/128, 1/256, 1/512}. The values of α_1 and α_2 used in individual sub-streams were determined experimentally, taking into account the results of encoding the set of test video sequences. The achievements of the VVC-CABAC technique are now a benchmark for research in the field of advanced entropy compression of video data.

C. ESTIMATION OF PROBABILITIES OF BINS – OTHER LITERATURE PROPOSALS OF IMPROVEMENTS

While it is not difficult to identify proposals for improvements that refer to older versions of the CABAC technique (e.g., many previous work by the author and other scientists [25], [26], [27], [28], [29], [30], [31], [32], [33], [34]), research in terms of the latest version of the technique (so VVC-CABAC) has just begun. Currently, it concerns further extensions of the concept of multi-parameter estimation of bins probabilities, which is used in VVC-CABAC.

In this context, in his earlier work, one of the author of this paper has proposed examples of such new extensions, analyzing their impact on the efficiency of the VVC-CABAC technique [35]. The author has investigated the effect of better adjustment of the values of parameters α_1 and α_2 to the nature of the encoded video content, the impact of considering the type of the encoded video frame in the procedure of selecting the values of α_1 and α_2 and the possibility of using dedicated weighting factors in sub-streams, according to which the statistics estimation algorithm averages the two probability values (obtained using parameters α_1 and α_2, respectively). The results of the conducted research indicated the possibility of additional reduction of the bitstream in the range of 0.08% - 0.2% (on average), compared to the efficiency of the original VVC-CABAC technique.

This article deals with a different idea of improving the algorithm, compared to the methods indicated above. An interesting solution that has started to be investigated recently is the symbol statistics estimation using more than two α parameters. An example of such research is [36], in which the application of probability estimation with the use of four parameters α is considered. The research results presented in the paper have shown very promising efficiency of such an approach, enabling the achievement of substantial bit savings in the representation of video data. This paper is a kind of extension of the research direction adopted in [36].

III. ARITHMETIC CODING EFFICIENCY

The bit cost of coding a single bin with the probability of occurrence $p\left(bin\right)$ can be estimated by formula (3), which is a correct methodology when evaluating the efficiency of arithmetic coding methods [38]:

$$Cost\left(bin\right) = -log_2(p\left(bin\right)) \quad [\text{bits}] \quad (3)$$

Thus, the total bit cost of encoding all bins is equal to:

$$Total\ bit\ cost = \sum\nolimits_{all\ bins} Cost\left(bin\right) \quad (4)$$

The goal of entropy coding is to get at its output as low as possible number of bits. Thus, the lower the obtained total bit cost value (see formula 4), the higher the efficiency of entropy compression. This efficiency can be also expressed by calculating the ratio of the number of resulted bits (*Total bit cost*) to the number '*number of bins*' of encoded bins (the so called *bits to bins ratio*), as realized by formula (5).

$$bits\ to\ bins\ ratio = \frac{Total\ bit\ cost}{number\ of\ bins} \tag{5}$$

Explanation of the sense of the above ratio is the following. The lower the ratio the higher efficiency of entropy data compression. A direct comparison of the *Total bit costs* or the '*bits to bins ratio*' obtained for two different variants of CABAC encoding allows us to determine the percentage difference in efficiency of compared variants.

IV. DETAILED GOALS OF THE WORK

The concept that was presented in the research [36] became the inspiration for the research presented in this work. The aim of this paper is to present an in-depth assessment of the validity of the use of multi-parameter probability estimation in the VVC-CABAC technique. In particular, the authors' research focuses on comparing the benefits of applying further improvements to the two-parameter estimation and the use of three- and four-parameter estimation. In each of the assumed cases, the appropriate research on the efficiency of a given solution will be preceded by the stage of selecting the best values of the method parameters (within the limits adopted in the methodology of experiments, presented in the following parts of the paper), taking into account the content of the encoded video sequence. The main aim of the research is to present results illustrating the limitations of further improvement of the efficiency of modern, advanced entropy coding techniques.

V. HIPOTETHICAL NEW VARIANTS OF VVC-CABAC WITH POTENTIALLY HIGHER EFFICIENCY

The advantage of the latest VVC-CABAC technique (compared to the earlier versions of AVC-CABAC and HEVC-CABAC) is the use of the concept of two-parameter probability estimation (instead of estimation based on only one parameter α). When working on objectives of this work, the authors consider the following extensions of this concept:

1) Two-parameter estimation with new values of α_1 and α_2 in each sub-stream of bins, dedicated to a content of video sequence,
2) Three-parameter estimation of probabilities, using dedicated values of parameters in individual sub-streams of bins and for a given video sequence,
3) Four-parameter estimation, with a dedicated set of parameters' values within individual sub-streams of bins and for a given video sequence.

In order to assess the real potential of each of the above proposals, the α parameters were, as stated above, recalculated by the authors, making them better adapted from the point of view of coding a given test video sequence. The factor that is of great importance here is the set of values from which α parameters were determined. In the study, each parameter was determined on the basis of the set: {1/4, 1/8, 1/16, 1/32, 1/64, 1/128, 1/256, 1/512}. The set of values used in the research is a combination of the two separate sets, which for parameters α_1 and α_2 are used in the original VVC-CABAC technique, which is the reference for the research of this work.

For each of the tested variants, it was assumed that the final probability of symbol occurrence would be a simple average of the probabilities obtained for a given parameter α (thus the same as with the original VVC-CABAC technique).

VI. METHODOLOGY OF ANALYSIS OF THE POTENTIAL OF THE VARIANTS CONSIDERED

A. MAIN ASSUMPTIONS

The subject of the experiments was the entropy data compression of syntax elements that occur in the VVC video compression technique.

In connection with the presented assumptions and a wide range of planned experiments, three sets of the authors' software were prepared (in C/C++). The first set is program code that is a CABAC bins' analyzer, which are subject to arithmetic coding in the VVC-CABAC technique. This software extracts sub-streams of bins (representing individual syntax elements) that are presented in VVC encoded bitstreams.

The second set of software performs CABAC entropy compression of the previously acquired bins, when using the indicated α parameter values. Additionally, the software measures the efficiency of this compression by calculating the number of bits produced by an entropy encoder, when operating with the specific α parameter settings. The software is using formula (4) for this purpose. On this basis, the software allows to test CABAC encoding for various settings of α and finally to select those that are optimal from the point of view of data compression efficiency.

The third set of software performs a CABAC compression of the data produced by the first software using the optimal α parameters determined by the second software.

Additionally, the third set of software measures the efficiency of data encoding (when using formula (4)). This research therefore focuses on assessing the efficiency of variants of the improved VVC-CABAC technique that apply previously determined, better adapted values of α. In a practical encoding scenario, the entropy compression of the data must be preceded by the step of α (or α_i) value calibration.

B. DETAILS OF SOFTWARE IMPLEMENTATION

The first program code was prepared on the basis of the VTM 7.2 software [37] of the VVC video decoder [9]. Taking into account the authors' modifications, this software performs decompression of the encoded video frames, retrieving from the encoded bitstream the data of syntax elements that were previously produced by the VVC video encoder during compression. For the purpose of further experiments, the obtained syntax elements are written to a set of files in such a way that one file contains bins that come from a given sub-stream. In addition, the files contain information about the number of the video frame from which the individual data comes.

In the next step, the prepared files are transferred to the second software. As mentioned earlier, its task is to select the best (in terms of coding efficiency) values of the α parameters for the set of data contained in files. This selection is made by encoding a file data multiple times, each time using different values of α parameters. The implementation of this task requires a proper assessment of the efficiency of entropy coding for a given set of parameters. This efficiency was assessed by cumulating the bit cost of entropy compression of successive data symbols (bins), using the probability values of these symbols obtained in the statistics estimation algorithm together with mathematical formula (4).

C. TEST VIDEO DATA

To realize the assumed goals of the work, the new VVC video coding technique was adopted as the testing ground [9], [10]. The first step of the research was to prepare encoded video bitstreams that are compliant with the VVC standard. To do this, a series of video encodings were performed using the VTM 7.2 software of the VVC and test video sequences: *BQTerrace*, *Cactus*, *Kimono1*, *ParkScene* (2K sequences) and *PeopleOnStreet*, *Traffic* (with spatial resolution of frames beyond 2K). An important element that may determine the results of experiments is the configuration of the video encoder. The aim was to conduct experiments in encoding conditions aimed at achieving high compression efficiency, a scenario that is typical for television on IP or TV-on-demand systems. Therefore, in the VTM 7.2 software, the 'random access' encoding scenario was adopted (see "common test conditions" recommendation of MPEG and VCEG [39]). This scenario implements sophisticated video encoding algorithms and therefore ensures obtaining very high efficiency of data compression. Following this recommendation, each of the test sequences was encoded four times, each time using a different value of the quantization parameter QP (QP = 22, 27, 32, 37). This parameter determines the "strength" of quantization of residual data of video frames prediction (expressed in the frequency domain), which translates significantly into the results of compression (encoded data stream size and video quality after compression and decompression), according to the rule: low QP value – high quality of a video and a large bitstream, high QP value – low quality of a video and a small bitstream. As a result, coded video bitstreams were obtained that contain real data of syntax elements that are finally subject to entropy compression in the new VVC video encoder.

VII. EXPERIMENTAL RESULTS

The use of the idea of multi-parameter estimation of probabilities leads to an increase in the efficiency of entropy coding. An important factor that influences this efficiency is, of course, the method of determining the values of the parameters. In each of the encoding variants studied in this work, we adopted values of α parameters that are optimal for a given video sequence (i.e., maximize the efficiency of data compression).

The research began by comparing the efficiency of the older version of CABAC, used in HEVC (that is based on a single-parameter estimation of probabilities), with the latest variant of VVC-CABAC technique, which is part of the new VVC technology (it exploits the two-parameter estimation of probabilities). The results of the experiments clearly showed the superiority of the latest solution. The use of significant improvements (compared to the older version of CABAC) made it possible to reduce the resulting bitstream by 0.77% and 0.81% in average, for set of 2K and beyond 2K test video sequences, respectively. The obtained data show the scale of difficulty of improving the efficiency of the CABAC technique, even in relation to the improvements made to the older version of this technique.

In the case of single-parameter estimation, a loss of coding efficiency was noted (with reference to the new VVC-CABAC technique), even with more accurate calibration of α. Depending on the content of the encoded video, it was a 0.1% - 0.32% increase of bitstream for 2K videos, and a 0.06% - 0.25% increase for videos with spatial resolution of frames beyond 2K. Thus, the use of only one α parameter in individual sub-streams, with values that are adapted to the content of the encoded video does not perform better than the original VVC-CABAC, that operates with α_1 and α_2.

The optimization of the two-parameter variant (the so-called '2 alphas-CABAC') allowed us to increase the efficiency of the original VVC-CABAC technique (by 0.09% and 0.12% on average, for 2K and beyond 2K video sequences, respectively). As one can see, the proper calibration of α parameters is an important element that determines noticeably the efficiency of the method.

The use of three- and four-parameter estimation (with optimization of parameters) produced even better results of data encoding. In relation to the original VVC-CABAC, the average gains of compression were 0.11% and 0.12%, respectively, for the three- and four-parameter estimation (for 2K videos). For sequences with a resolution higher than 2K, it was approximately 0.16% in each case. A detailed analysis of partial results shows the range of bitrate reduction obtained for the tested set of video sequences. It was 0.07% - 0.18% and 0.08% - 0.19%, respectively, for the three- and four-parameter estimation. Sequences with higher spatial resolution produced noticeably different ranges of coding gain: 0.09% - 0.21% for the three-parameter estimation and 0.1% - 0.22% for the four-parameter estimation.

When analyzing the results of the experiments, it can be observed that more favorable results were obtained for videos with higher spatial resolution of frames. This applies to each of the considered coding variants (see tables with detailed results). According to experience of the authors, the frequency of resetting the entropy encoder settings (entropy encoder initialization) has a significant impact on the efficiency of data encoding. It becomes the lower, the more frequently this reset occurs. In the adopted research scenario, resetting was performed at the beginning of each frame of a video. Video frame of a higher spatial resolution contains a larger set of entropy-encoded data, which allowed the entropy encoder to "learn" better the statistics of the data. Hence, the higher efficiency of the solutions considered in this paper was

TABLE 1. Results of experiments for 2K test video sequences.

		original algorithms			considered variants of modified VVC-CABAC				bitrate increase [%]			
		bits to bins		bitrate increase [%]	bits to bins				1 alfa-CABAC to VVC-CABAC	2 alfas-CABAC to VVC-CABAC	3 alfas-CABAC to VVC-CABAC	4 alfas-CABAC to VVC-CABAC
2K video		HEVC-CABAC	VVC-CABAC	HEVC-CABAC to VVC-CABAC	1 alfa-CABAC	2 alfas-CABAC	3 alfas-CABAC	4 alfas-CABAC				
BQTerrace	QP = 22	0.64553	0.64072	0.75072	0.64179	0.64016	0.64007	0.64001	0.16638	-0.08740	-0.10207	-0.11034
	QP = 27	0.69280	0.68758	0.75889	0.68909	0.68702	0.68686	0.68679	0.21903	-0.08101	-0.10457	-0.11548
	QP = 32	0.72019	0.71438	0.81372	0.71609	0.71369	0.71345	0.71336	0.23979	-0.09659	-0.13004	-0.14250
	QP = 37	0.71241	0.70664	0.81640	0.70819	0.70576	0.70547	0.70538	0.21921	-0.12383	-0.16515	-0.17859
Cactus	QP = 22	0.67022	0.66529	0.74133	0.66673	0.66485	0.66471	0.66464	0.21615	-0.06629	-0.08718	-0.09755
	QP = 27	0.72361	0.71788	0.79846	0.72006	0.71756	0.71739	0.71730	0.30270	-0.04527	-0.06840	-0.08177
	QP = 32	0.72541	0.71962	0.80403	0.72194	0.71924	0.71901	0.71892	0.32142	-0.05350	-0.08560	-0.09755
	QP = 37	0.71945	0.71395	0.77135	0.71624	0.71344	0.71320	0.71308	0.32145	-0.07073	-0.10505	-0.12088
Kimono1	QP = 22	0.71176	0.70630	0.77333	0.70741	0.70564	0.70549	0.70543	0.15758	-0.09302	-0.11440	-0.12233
	QP = 27	0.72130	0.71597	0.74444	0.71692	0.71513	0.71495	0.71490	0.13269	-0.11830	-0.14316	-0.15028
	QP = 32	0.71107	0.70601	0.71628	0.70674	0.70504	0.70486	0.70479	0.10354	-0.13838	-0.16374	-0.17294
	QP = 37	0.69490	0.69024	0.67556	0.69094	0.68923	0.68900	0.68894	0.10127	-0.14560	-0.17921	-0.18863
ParkScene	QP = 22	0.71304	0.70727	0.81681	0.70893	0.70687	0.70671	0.70666	0.23513	-0.05656	-0.07861	-0.08611
	QP = 27	0.71657	0.71069	0.82765	0.71228	0.71019	0.71003	0.70997	0.22415	-0.07049	-0.09287	-0.10187
	QP = 32	0.70908	0.70345	0.80120	0.70499	0.70293	0.70275	0.70269	0.21978	-0.07278	-0.09923	-0.10790
	QP = 37	0.69661	0.69123	0.77920	0.69274	0.69068	0.69048	0.69041	0.21845	-0.07899	-0.10807	-0.11863
			Average:	**0.77433**				Average:	**0.21242**	**-0.08742**	**-0.11421**	**-0.12458**
				lower efficiency of HEVC-CABAC					**lower efficiency** of '1 alfa-CABAC'	**higher efficiency** of 'x alfas-CABAC'		

TABLE 2. Results of experiments for test video sequences with spatial resolution of video frames beyond 2K.

		original algorithms			considered variants of modified VVC-CABAC				bitrate increase [%]			
		bits to bins		bitrate increase [%]	bits to bins				1 alfa-CABAC to VVC-CABAC	2 alfas-CABAC to VVC-CABAC	3 alfas-CABAC to VVC-CABAC	4 alfas-CABAC to VVC-CABAC
>2K video		HEVC-CABAC	VVC-CABAC	HEVC-CABAC to VVC-CABAC	1 alfa-CABAC	2 alfas-CABAC	3 alfas-CABAC	4 alfas-CABAC				
PeopleOnStreet (3840x2160)	QP = 22	0.72490	0.71901	0.81946	0.72052	0.71826	0.71805	0.71799	0.21071	-0.10361	-0.13324	-0.14131
	QP = 27	0.74526	0.73920	0.82008	0.74041	0.73817	0.73793	0.73787	0.16410	-0.13880	-0.17248	-0.17965
	QP = 32	0.74803	0.74216	0.79012	0.74314	0.74102	0.74073	0.74069	0.13151	-0.15401	-0.19308	-0.19780
	QP = 37	0.74625	0.74069	0.75187	0.74146	0.73949	0.73921	0.73918	0.10409	-0.16188	-0.19887	-0.20387
PeopleOnStreet (2560x1600)	QP = 22	0.74102	0.73487	0.83702	0.73617	0.73393	0.73368	0.73362	0.17677	-0.12791	-0.16261	-0.16996
	QP = 27	0.75325	0.74718	0.81252	0.74809	0.74604	0.74573	0.74569	0.12072	-0.15338	-0.19406	-0.19982
	QP = 32	0.75274	0.74698	0.77151	0.74763	0.74570	0.74540	0.74536	0.08662	-0.17109	-0.21112	-0.21754
	QP = 37	0.75172	0.74631	0.72503	0.74674	0.74498	0.74470	0.74465	0.05695	-0.17808	-0.21559	-0.22256
Traffic (3840x2048)	QP = 22	0.71853	0.71222	0.88667	0.71397	0.71164	0.71143	0.71138	0.24684	-0.08017	-0.11008	-0.11682
	QP = 27	0.72378	0.71766	0.85403	0.71942	0.71713	0.71695	0.71688	0.24524	-0.07385	-0.09796	-0.10785
	QP = 32	0.72327	0.71732	0.82947	0.71902	0.71674	0.71655	0.71647	0.23629	-0.08169	-0.10748	-0.11891
	QP = 37	0.71496	0.70916	0.81759	0.71088	0.70854	0.70833	0.70826	0.24198	-0.08757	-0.11760	-0.12677
			Average:	**0.80961**				Average:	**0.16848**	**-0.12600**	**-0.15952**	**-0.16691**
				lower efficiency of HEVC-CABAC					**lower efficiency** of '1 alfa-CABAC'	**higher efficiency** of 'x alfas-CABAC'		

observed for such video sequences. The efficient initialization of encoder settings is another important component of the entropy coding technique.

VIII. SUMMARY AND FINAL CONCLUSION

The multi-parameter estimation of probabilities is the basis of modern, high-performance arithmetic coding methods. This concept has become part of the latest version of CABAC (called VVC-CABAC) used in the new VVC video encoder. In this case, an algorithm of two-parameter estimation of probabilities was used. In terms of data compression efficiency, the new VVC-CABAC technique clearly outperforms the older versions of CABAC encoding (those used in the AVC and HEVC techniques), which were based on a less accurate estimate of a one-parameter model. Detailed results of such a comparison were presented in this paper.

The above conclusion is therefore a kind of guide for the future research. A question arises at this point about the possibility of further extending the above idea towards the use of even more parameters (more than just two) in the algorithm of estimation of probabilities. At this point, the same method of determining the values of parameters is also important. The indicated problems were the subject of research in this work.

The authors investigated the possibility of using three- and four-parameter estimation in VVC-CABAC. The point of reference for these studies were encoding variants that use one or two parameters. In each of the considered cases, the aim was to check the real potential of data compression. Therefore, the research on encoding efficiency was preceded by the selection of the optimal parameter values (in terms of compression efficiency of a given video sequence). The obtained results of experiments made it possible to formulate general conclusions.

Encoding with one-parameter estimation algorithm is characterized by a lower coding efficiency than that recorded for the VVC-CABAC technique (by 0.21% and 0.16% on average, for 2K and beyond 2K video sequences). However, the recorded loss of efficiency is lower than that observed for the case of the HEVC-CABAC technique (which is also based on one-parameter calculation of probabilities). It indicates the high importance of the method of selecting the values of parameters from the viewpoint of efficiency of entropy compression.

In the case of two-parameter estimation algorithm, a better calibration of the values of α_1 and α_2 in individual data sub-streams resulted in an improvement in efficiency (in relation to the original VVC-CABAC) by about 0.1%. Three- and four-parameter estimation further improves this efficiency, ultimately ensuring coding gains of up to 0.2% (0.11% - 0.16% on average). The obtained results justify the use of a higher number of α parameters in the mechanism of data symbol probability estimation in the future.

The research focused on entropy data compression of syntax elements that are observed in the latest hybrid video encoder: VVC. In the highest percentage those elements represent the residual prediction signal of other data and is usually zero or very small value. Accurate determination of the statistics of such a signal is extremely difficult, as shown in the results of the comparison of efficiency of the VVC-CABAC and HEVC-CABAC techniques – the use of a far more advanced probability estimation mechanism improved the efficiency by (only) 0.77% - 0.8% on average. In studies that refer to the new VVC-CABAC technique (as in the case of this paper), achieving any improvement in compression efficiency is even more difficult, as shown by the results of the authors' experiments.

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