Improved Adaptive Arithmetic Coding for HEVC Video Compression Technology*

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Abstract. The paper presents Improved Adaptive Arithmetic Coding algorithm for application in forthcoming HEVC video compression technology. The proposed solution is based on standard CABAC algorithm and uses author's new mechanism of data statistics modeling that is based on CTW technique. The improved CABAC algorithm is characterized with better compression performance relative to standard CABAC. In the framework of HEVC encoder 1.6% - 4.5% bitrate reduction was obtained when using improved CABAC instead of the original algorithm.

Keywords: Adaptive arithmetic coding, improved CABAC, HEVC

1 Introduction

Entropy coding technique is an essential part of contemporary video encoders [4, 5, 11]. It plays significant role, because it further increases efficiency of encoder by reducing statistical redundancy of residual data. It made up the motivation for researchers to find solutions for more and more efficient entropy coding of data that lead to elaborating many new entropy coding techniques [1, 11, 12].

The state-of-the-art entropy coding technique used in video compression is the Context-based Adaptive Binary Arithmetic Coding (CABAC) [1, 5] that became a part of international video coding standard MPEG-4 AVC/H.264 [4]. Due to application in CABAC of advanced mechanisms of data statistics estimation, it was well experimentally proved, that CABAC algorithm outperforms other entropy encoders in terms of coding efficiency [1].

Currently, the works are in progress towards next, more efficient video compression technology High Efficiency Video Coding (HEVC) that are carried out under auspices of ISO/IEC MPEG and ITU VCEG [6, 9]. The works are in a final phase. General architecture of HEVC is already fixed and it is certain now that entropy coding of HEVC will be based on CABAC algorithm.

It was experimentally proved that compression performance of HEVC encoder is superior relative to efficiency of MPEG-4 AVC encoder (up to 20%-40% reduction of bitrate [13] for comparable quality of images). The question arises

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whether it is possible to further improve compression performance of HEVC technology by application of even more sophisticated entropy coding methods. Author proposes improved version of CABAC algorithm within HEVC and presents experimental results of its coding efficiency in reference to efficiency of the original HEVC with unmodified CABAC. Detailed methodology of experiments, results and important conclusions are also presented in the paper.

2 HEVC video compression technology - overview

The HEVC technology, like previous standards [4, 11], is based on hybrid coding scheme with motion-compensated prediction, transform coding and entropy coding of residual data. Nevertheless, there are many improvements and new coding tools that distinguishes the HEVC from other existing solutions and lead to extraordinary compression performance of video encoder.

The HEVC uses new coding structure by introducing the coding unit (CU), prediction unit (PU) and transform unit (TU) to perform prediction and adaptive coding of data in blocks of multiple sizes. In general, CU (the basic unit of image splitting) can have the size of 64x64 to 8x8. The PU (contains information related to prediction process) is sub-element of CU and can have its dimensions or can be as small as 8x4 or 4x8. The TU (unit used for transform and quantization processes) can be a square shape with sizes from 4x4 up to 32x32, or can be non-square shape with sizes 32x8, 8x32, 16x4, 4x16 when the PU is also non-square. The new coding structure allows choosing the size of block for prediction and transform in an adaptive manner exploiting local features of an image. Additionally, HEVC uses numerous intra- predictors and inter prediction of high precision within PU units when forming the residual data. In this way, transform coding approach is efficiently realized on highly correlated residual data.

Hybrid coding scheme introduces some artifacts into images, especially for high compression scenario. Therefore, reconstructed images are processed with in-loop filters (deblocking filter, sample-adaptive offset filter and adaptive loop filter) in order to improve subjective quality of decoded images [6]. The filters increases efficiency of inter-frame encoder also, due to the reference frames are more similar to the predicted frame.

Compression techniques described above lead to low-energy residual data. This data is efficiently coded using Context-based Adaptive Binary Arithmetic Coding (CABAC) as an entropy encoder. The CABAC algorithm used in HEVC is discussed in the next section in more details.

3 Entropy coding in HEVC - CABAC algorithm

The HEVC video compression technology uses Context-based Adaptive Binary Arithmetic Coding (CABAC) entropy encoder, which is a modified version of CABAC encoder that is used in MPEG-4 AVC/H.264 video compression standard. In order to limit computational complexity of HEVC CABAC codec, the number of statistical models was significantly reduced relative to version of

CABAC used in MPEG-4 AVC. Nevertheless, general idea of entropy codec remains the same and it was already described in details in the literature [1, 5]. Therefore, only main features of CABAC will be presented in the paper that are important from the point of view of improvements made by the author. CABAC realizes entropy coding of data with the use of adaptive arithmetic encoder that allows to efficiently represent input symbols by exploiting statistics of coded data. The general block diagram of CABAC encoder was presented in Fig. 1. The distinctive feature of CABAC algorithm is application the binary arithmetic codec core that is able to encode binary symbols from two elements alphabet only $A=\{0,\ 1\}$. Such an approach reduces complexity of entropy codec significantly - there exists fast realizations of binary arithmetic codec cores [5]. Application the binary arithmetic codec core in CABAC put requirement to translate all m-ary data symbols into string of binary symbols. This task is done by binarizer at the first stage of entropy coding. The way in which the binarizer works significantly affects the number of resulted binary symbols - it determines both the compression efficiency and the computational complexity of entropy codec. Therefore, the binarizer of CABAC uses several different binarization schemes that are adapted to specific statistics of individual syntax elements [1, 5]. This step can be understood as adaptive variable-length coding (VLC).

Binary symbols in a binarized word still exhibit some statistical redundancy. Therefore CABAC, in contrary to traditional VLC, additionally encodes binary symbols using arithmetic encoder core with taking into consideration the statistics of symbols. The way in which these statistics are calculated significantly influences compression performance of the whole entropy encoder and its com-

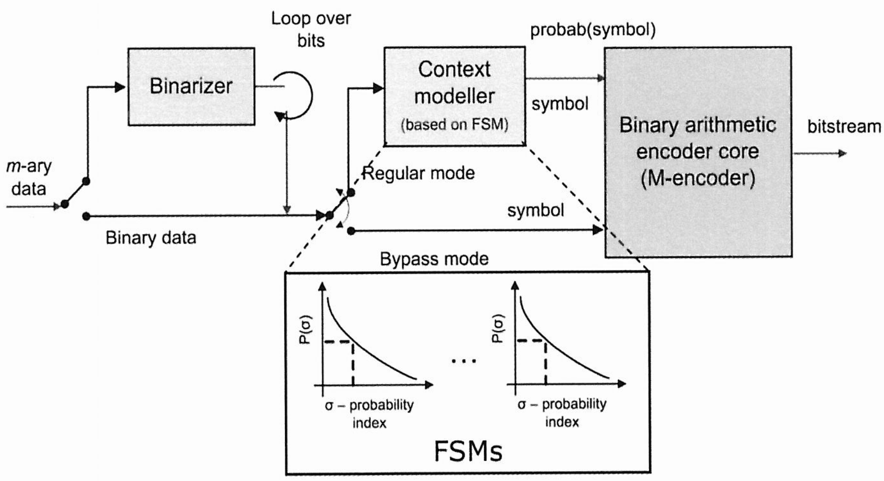

Fig. 1. General block diagram of CABAC encoder.

plexity. In order to trade off the two aspects, total number of 225[1] different statistical models were defined in CABAC within HEVC [14] (in HM 3.2 version of the software) to efficiently represent transform coefficients, motion and control data. In general, individual syntax elements of HEVC are characterized with different probability distribution - it is worth to track these statistics independently in entropy encoder for individual data types. To take above mentioned into consideration, CABAC assigns independent sets of statistical models to individual syntax elements. It makes the first level of CABAC adaptation to current signal statistics. Additionally, statistics of coded data locally changes within an image - the proper statistical model (from a set of models) should be chosen based on the context data (values of a given syntax element in neighboring blocks). This makes the second level of the encoder adaptation to statistics of coded data. In this way, conditional probability of a symbol is calculated based on the type of coded syntax element as well as its values in neighboring image blocks.

Author's results revealed that accurate estimation of data statistics is a very time-consuming task (more than 60% complexity of entropy codec [15]). CABAC introduces two essential simplifications in order to speed up computations. First of all, for each statistical model, probabilities of symbols are calculated in a simplified way using pre-defined Finite State Machine (FSM) with 64 states only that represent some value of a symbol probability [1, 5]. Secondly, some symbols are encoded in the so-called bypass coding mode with no data statistics modeling stage.

4 Research problem

Simplifications that were made in the CABAC's context modeler block significantly reduces accuracy of symbols' probabilities. It obviously negatively affects compression performance of CABAC.

In the past, it was the motivation for author to propose improved version of CABAC algorithm with more accurate data statistics estimation based on Context-Tree Weighting (CTW) method [2, 3]. Previous versions of improved CABAC were activated in the framework of MPEG-4 AVC video codec and tested in depth. Detailed experimental results revealed the possibility of reducing the bitrate by 2-8% when using improved version of CABAC instead of the original algorithm [7, 8].

The question arises to what extent more accurate mechanism of data statistics estimation in CABAC will lead to reduce the bitrate in the state-of-the-art HEVC technology. This paper answers this question. It presents tuned version of the improved CABAC (also based on CTW) with better algorithm of statistical models initialization and mechanism of its selection adapted to character of data coded in currently working out HEVC video compression technology.

[1] The number of statistical models is not fixed yet. There are still new proposals toward limiting the number of necessary models in CABAC within HEVC.

5 Improved version of CABAC algorithm in HEVC

The main idea of the improved CABAC is using more accurate mechanism of data statistics estimation, relative to the original algorithm. The motivation for such an approach is to calculate conditional probabilities of symbols more precisely in the context modeler block. Previous author's results obtained in the context of MPEG-4 AVC revealed, that it can be successfully done when using well-known in compression the Context-Tree Weighting (CTW) method [7, 8].

Starting point to research was the version of CABAC algorithm used in the framework of HEVC encoder (HM 3.2 version of the software). Simplified mechanism of probabilities estimation used in original CABAC (based on FSMs) was replaced by more sophisticated one exploiting CTW technique. Other functional blocks of CABAC (binarizer and binary arithmetic encoder core) were left unchanged. General block diagram of the improved CABAC was presented in Fig. 2. In improved CABAC, the CTW method is used by every statistical model to calculate conditional probabilities of symbols more exactly. In this way, improved CABAC uses 225 different context trees. The probabilities are calculated with respect to symbols that have been coded earlier - it means with respect to context information. The CTW algorithm uses binary context tree of depth D to store information on statistics of previously coded data that appeared in a given context. The general idea behind CTW is to calculate conditional probability of a current symbol with respect to context data of lengths from 0 to D. In the case of non-stationary data it is unknown which context length is the best to calculate probability of a symbol. Therefore, the CTW method appropriately weights probabilities calculated in different context lengths to produce final conditional probability that is used by arithmetic encoder core. More detailed description of CTW algorithm can be found in [2, 3, 11].

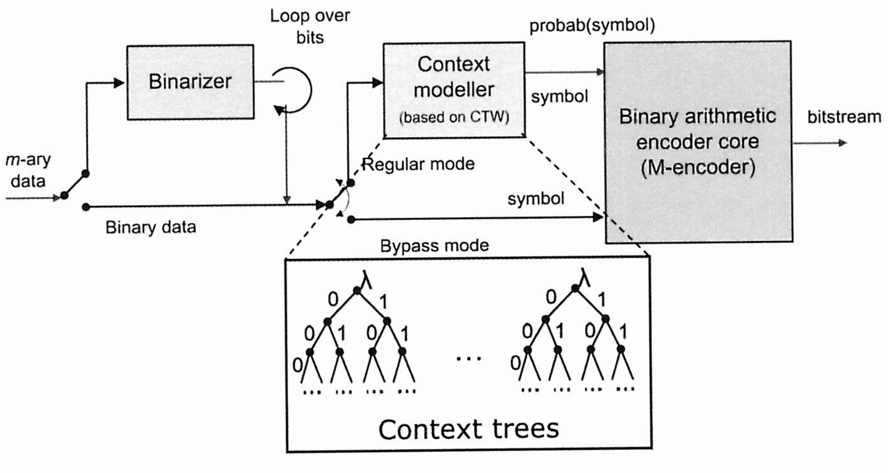

Fig. 2. Block diagram of the improved CABAC with more advanced context modeler.

Depth D of context trees influences precision of calculated probabilities. In general, the higher value of D the better efficiency of CTW technique. Thorough research made by author in the framework of MPEG-4 AVC revealed, that D=8 makes good compromise between efficiency and complexity of entropy codec. Such a depth of context trees was also assumed in presented version of the improved CABAC.

Two different versions of the improved CABAC were elaborated: first, with smaller number of statistical models for transform coefficients and binarization scheme based on concatenation of truncated unary code, truncated Golomb-Rice code and 0th order Exp-Golomb code [12], and second, with bigger number of statistical models for transform coefficients and binarization scheme based on concatenation of truncated unary code and 0th order Exp-Golomb code [1]. In both versions of the improved CABAC new mechanism of statistical models initialization was used. The mechanism exploits the idea of extended frame slice (slice that contains more than one image frame) that allows carrying statistics of coded data between neighboring frames of the same type.

6 Efficiency of the improved HEVC - methodology

Both versions of the improved CABAC codec (encoder and decoder) were fully implemented in C++ programming language. In order to obtain reliable experimental results, both the encoder and decoder parts were implemented. Improved entropy codecs were put and activated in the structure of HEVC video codec (encoder and decoder). The starting point for implementation was the reference software of HEVC known as HEVC test model (HM 3.2) [14]. Coding efficiency of the improved HEVC encoder (with improved CABAC) was explored and referenced to efficiency of original HEVC with standard CABAC algorithm. In particular, experiments were done according to the following scenario:

- HD and full HD test video sequences were used: *Station2* (1920x1080), *River Bed* (1920x1080), *Pozna Street* (1920x1088), *Balloons* (1024x768), *China Speed* (1024x768), *Slice Editing* (1280x720). Two of them (*China Speed* and *Slice Editing*) are synthetic and screen content sequences.
- The IBBBB structure of group of pictures (GOP) was used.
- Tests were done for a wide range of bitrates using values of quantization parameters (QP) equal to 22, 27, 32, 37. In this way experiments were done for quality of reconstructed videos from excellent to poor.
- Rate-distortion control mechanism was based on adaptive VLC codes.
- Other settings used: motion estimation based on Enhanced Predictive Zonal Search (EPZS) method, search range equal to 64, loop filters enabled.

With reference to the original HEVC, efficiency of the improved encoder was measured using known in video compression Bjøntegaard metric [10]. Bjøntegaard metric enables comparison of rate-distortion (RD) curves of two encoders in terms of average bitrate reduction based on several RD points. In the paper, average bitrate reduction was calculated based on 4 RD points (for QP=22, 27, 32, 37) for luma component.

7 Efficiency of the improved HEVC - results

Experimental results proved that application of the improved CABAC within HEVC increases compression performance of video encoder. Average bitrate reduction calculated for different test sequences using Bjøntegaard metric were presented in Table 1 for both the first and the second version of the improved CABAC. On average, 2.6% bitrate reduction was obtained for used video sequences. Content and character of a video sequence significantly affects compression results. Better results were observed in the case of sequences containing computer graphics and screen content (*China Speed* and *Slice Editing*) with up to 4.5% and 3.6% bitrate reduction respectively. It results from the fact, that CABAC algorithm was adapted to efficiently encode images that represent natural scenes - it is characterized with limited level of adaptation to real statistics of data. Improved CABAC algorithm is featured with higher level of adaptation to current signal statistics. Therefore, the gap between the improved and the original CABAC is bigger in such cases. Smaller gain was observed in the case of natural scene sequences with bitrate reduction between 1.6% and 3%.

Application of more advanced entropy codec within HEVC affects its computational and memory complexity. The use of the improved CABAC increases complexity of HEVC decoder by a factor of 1.34 (for 3 Mbps scenario) and 1.1 (for 0.5 Mbps scenario) in comparison to the original HEVC with standard CABAC. Improved CABAC also increases memory requirements - memory space needed to store all context trees is about 0.5 MB.

8 Conclusions and final remarks

Compression performance of forthcoming HEVC technology can be further increased when using improved entropy encoder. Better mechanism of data statistics estimation in CABAC leads to 1.6% - 4.5% reduction of HEVC bitstream. This compression gain is occupied with higher complexity of the video codec.

Table 1. Average bitrate reduction due to application of the improved HEVC (**version 1** and **version 2**) relative to the original HEVC. Individual versions of the improved CABAC differs from number of statistical models and methods of binarizations.

Test sequence	**Average bitrate reduction** (**1st ver.** of improved HEVC)	**Average bitrate reduction** (**2nd ver.** of improved HEVC)
Station2	1.78%	1.77%
River Bed	2.90%	3.02%
Poznan Street	2.21%	1.62%
Balloons	2.15%	1.64%
China Speed	4.50%	2.91%
Slice Editing	3.39%	3.57%
Average	**2.82%**	**2.42%**

Obtained results indicate that it is more and more difficult to increase efficiency of successive generations' video encoders by tuning the entropy encoders. In adequate research performed by author in the framework of AVC, higher gains were achieved [7, 8]. Successive generations of video encoders exploits more efficient mechanisms of signal prediction which, in general, leads to residual signal of a smaller energy. Accurate estimation of statistics for such signal is a real problem that limits possibilities of efficient entropy coding the data.

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