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Fast Adaptive Binary Arithmetic Coding (M Coder)

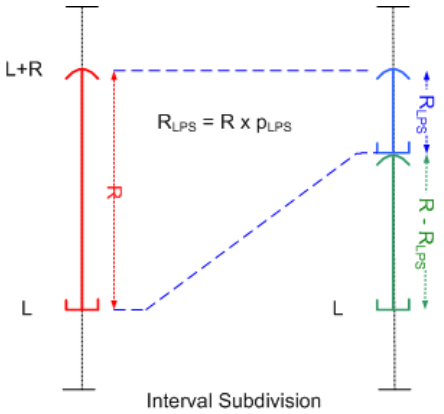
Overview: A novel design of a family of fast table-based adaptive binary arithmetic coders has been designed. This so-called *M coder* involves the innovative features of a table-based interval subdivision in conjunction with a fast and accurate table-based probability estimator and a fast bypass coding mode. The computational critical operation of interval subdivision is approximated by using a pre-quantization of the range of admissible interval width values induced by renormalization. Then, for each quantization interval and for each representative probability value, the corresponding product value is pre-calculated and stored with suitable precision into a 2-D lookup table. Probability estimation is performed by employing a finite-state machine with tabulated transition rules. For approximately uniformly distributed sub-sources, an optional bypass of the probability estimator results in an additional speed-up.

A member of the M-coder family has been adopted as a normative part of the H.264/AVC CABAC entropy coding scheme. This M-coder variant in H.264/AVC provides virtually the same coding efficiency as a conventional multiplication- and division-based implementation of binary arithmetic coding at significantly higher throughput rates corresponding to speed-up factors in the range of 1.5-2.5. Compared to the MQ coder (as part of JBIG2 or JPEG2000), an increase in throughput of up to 18% can be achieved, depending on the implementation platform. At the same time, the M coder obtains average bit rate savings of 2-4 % relative to the MQ coder in its native H.264/AVC CABAC environment.

Background: The discovery of arithmetic codes using a finite-precision arithmetic, independently achieved by RISSANEN and PASCO in 1976, can be considered as the origin of practical arithmetic coding. Since that time many researchers have contributed to the evolution of arithmetic coding as a purely academic research topic towards a practical coding method. The main advantages of arithmetic codes compared to the more popular variable-length codes (VLCs) can be summarized as follows.

- ***Entropy approximation***: Arithmetic coding allows to assign a non-integer number of bits to each symbol to encode and therefore, it is able to generate a code with a compression performance that comes arbitrary close to the theoretical lower bound.
- ***Adaptivity***: The usage of relatively simple adaptation mechanisms enables an arithmetic coder to adapt to the underlying source statistics.
- ***Higher-order modeling***: Due to a simple interface between arithmetic coding and statistical modeling, higher-order statistical redundancies can be efficiently removed by the usage of appropriately designed context models.

However, compared to VLCs, the usage of arithmetic codes, in general, involves much higher computational costs due to the inherently sequentially organized operation of recursive interval subdivision. Moreover, in an adaptive coding approach, there is the closely related task of estimating the symbol probabilities based on previously encoded/decoded symbols, which generally results in additional nontrivial computational complexity. Although numerous fast variants of adaptive *binary* arithmetic coding were invented and implemented into practical coding schemes, there is an enduring interest in developing more efficient variants of arithmetic coding that enable even better or more flexible compromises between coding efficiency and implementation cost.



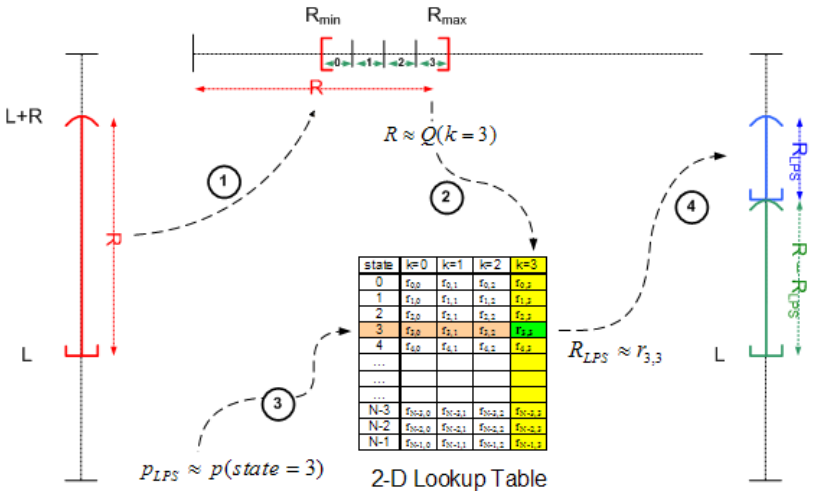
(MPS). By keeping track of the value of the MPS (valMPS) and the probability value of the LPS, denoted as p_{LPS}, a simple parametrization of the underlying binary alphabet is achieved. Based on that setting, an initially given interval (as shown in the figure above), which is represented by its lower bound (base) L and its width (range) R is subdivided into two disjoint subintervals: one interval of width $R_{LPS} = R \times p_{LPS}$, which is associated with the LPS, and the dual interval of width $R_{MPS} = R - R_{LPS}$, which is assigned to the MPS. Depending on the binary value to encode, either identified as the LPS or the MPS, the corresponding subinterval is then chosen as the new coding interval. By recursively applying this interval-subdivision scheme to each element b_j of a given sequence of binary decisions $\mathbf{b} = (b_1, b_2, \ldots, b_N)$, the encoder finally determines a value $c_{\mathbf{b}}$ in the final subinterval $[L^{(N)}, L^{(N)} + R^{(N)})$ that results after the N^{th} interval subdivision process. The (minimal) binary representation of $c_{\mathbf{b}}$ is the arithmetic code of the input sequence **b**. To ensure that finite-precision registers are sufficient to represent $R^{(j)}$ and $L^{(j)}$ for all $j \in \{1,2, \ldots, N\}$, a *renormalization* operation is required, whenever $R^{(j)}$ falls below a certain limit after one or more interval subdivision process(es). By renormalizing $R^{(j)}$, and accordingly $L^{(j)}$, the leading bits of the arithmetic code can be output as soon as they are unambiguously identified.

On the decoder side, the sequence of encoded binary values can be easily recovered by tracking the interval subdivision step-by-step and by comparing the bounds of both subintervals to the transmitted binary value of $c_{\mathbf{b}}$ representing the final subinterval. Note that the width $R^{(N)}$ of the final subinterval is proportional to the product $\prod_{j=1}^{N} p(b_j)$ of the individual probabilities of the elements b_j of the binary sequence, such that for signaling the final subinterval, the lower bound of the empirical entropy of the binary sequence given by $-\log_2 \prod_{j=1}^{N} p(b_j) = -\sum_{j=1}^{N} \log_2 p(b_j)$ is approximately achieved.

From the standpoint of computational complexity, the most critical drawback of a straightforward implementation of arithmetic coding is the multiplication or even division operation required to perform the interval subdivision in integer arithmetic for each symbol to encode/decode. Usually, integer multiplications/divisions are quite expensive operations, especially when realized in hardware. Therefore, most of the research work in the literature dealing with the topic of fast binary arithmetic coding is devoted to the problem of employing a suitable approximation of the multiplication $R \times p_{LPS}$ for determining R_{LPS}. The published work in the literature can be roughly divided into two categories as follows.

Prior work on fast binary arithmetic coding: The first category of published work on multiplication-free interval subdivision is based on the idea to approximate either the estimated probabilities p_{LPS} or the interval width R in such a way that the multiplication can be replaced by one or more shifts and adds. Therefore, this class of coders are denoted as the *shift-and-add coders*. Two typical representatives of this class are the *shift coder* of LANGDON and RISSANEN and the *CKW scheme* of CHEVION et al. While in the former approach p_{LPS} is confined to negative integral powers of 2, the latter relies on an approximation of the form $\frac{1}{2} + r$, where $r \in \{2^{-k} \mid k \in |N\}$ for the entire range of admissible values for the interval width R. In general, however, there is a rather strong imbalance between the amount of complexity reduction typically achieved by a shift-and-add coder and the observed degradation in coding efficiency due to the rough approximations involved.

The second and main category of published research work summarizes all binary arithmetic coding algorithms that are based on the more radical approach of performing the interval-subdivision process by means of table-lookup operations only. The most prominent representatives of this so-called class of *table-driven coders* are given by the *Q coder* (PENNEBAKER et al.) and its variants *QM* and *MQ* coder, as adopted by JPEG and JPEG2000, respectively. Other techniques belonging to this class are the *quasi-arithmetic coder* (HOWARD and VITTER), the *Z coder* (BOTTOU), and the *ELS coder* (WITHERS). As a common characteristic feature of these table-driven arithmetic coders, a *finite-state machine* (FSM) is employed for estimating binary symbol probabilities.



Proposed M Coder: The basic idea of the proposed low-complexity approach of interval subdivision is to quantize the range of possible interval width values induced by renormalization into a small number of K cells [JVT-C061]. To further simplify the calculations required to determine quantizer indices, a uniform quantization with $K = 2^k$ is assumed to be performed, resulting in a set $\mathcal{Q} = \{Q_0, Q_1, \ldots, Q_{K-1}\}$ of representative interval widths. Together with the representative set of LPS-related probability values of the FSM given by $\mathcal{P} = \{p_0, p_1,$

addressed by the (probability) state index n and the quantization cell index k(R) related to the given value of R, as illustrated above. Computation of the quantizer index k(R) is easily carried out by a concatenation of a bit-shift and a bit-masking operation, where the latter can be interpreted as a *modulo operation* using the operand $K = 2^{\kappa}$, hence the naming 'modulo coder' or briefly 'M coder' of the proposed two-parameter family of coders.

For a fixed choice of the FSM-based estimator, which means that P and N are selected beforehand, the corresponding family of modulo coders can be parameterized by κ. Usually, only small numbers of $\kappa \in \{0,1,2,3\}$ are of practical relevance, since the size of the lookup table is growing exponentially in κ. Larger values of κ result in a higher accuracy of the representation of R, but they require also larger lookup tables. In most practical cases, the choice of a suitable κ and the selection of an appropriate probability estimator has to be simultaneously optimized. For H.264/AVC the optimal choice of the free parameters κ and N was determined under the constraint for the lookup table size of $2^{\kappa} \cdot N \leq 256$ bytes, where each table entry was represented with an 8-bit integer precision. Obviously, the optimization process depends on the statistical nature of the given data. For a representative test set of video sequences encoded under different coding conditions within the H.264/AVC video coder, a configuration of (κ, N) = (2,64) was found to be optimal. This configuration is used for the standardized M coder variant of H.264/AVC. Note that the case κ = 0 is conceptually equivalent to the Q coder approximation. Hence, the M coder concept can be considered as a generalization of the Q coder and its derivatives of QM and MQ coder.

Additional speed-up can be obtained by using a bypass of the probability estimation for approximately uniformly distributed binary symbols. This kind of sources is often observed in transform coders, where, e.g., signs of transform coefficients or least significant bits of absolute values of quantized transform coefficients can be assumed to be uniformly distributed. Therefore, the M coder contains a simplified interval subdivision in the so-called *bypass coding mode* based on a hard-wired equipartition. In this way, the whole bypass encoding/decoding process (including renormalization) can be realized by nothing more than a shift, a comparison, and for half of the symbols an additional subtraction.

Performance evaluation of the M Coder: In a set of coding experiments, the relative performance of the M coder in comparison to the MQ coder and to a conventional binary arithmetic coder has been evaluated in the CABAC environment of H.264/AVC. As a first remarkable outcome of these experiments, it was observed that in terms of coding efficiency, the specific M coder implementation of H.264/AVC achieves virtually the same performance in terms of coding efficiency as an implementation of conventional binary arithmetic coding based on multiplication and division operations in 16-bit integer arithmetic.

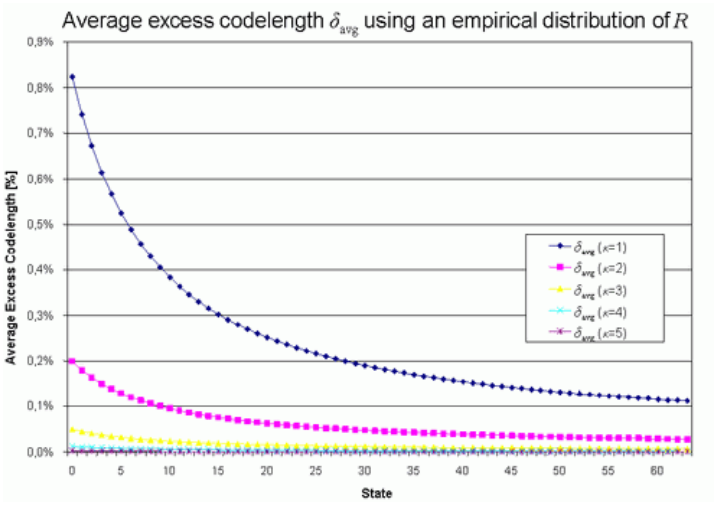
This experimental observation can be interpreted as a verification of the following analytical study of the approximation effects in the interval subdivision process. As a measure of inefficiency caused by the subdivision approximation, the so-called *excess codelength* or *relative entropy* D(p,p') is given as follows:

$$D(p,p') = -p \log_2 \frac{p'}{p} - (1-p) \log_2 \frac{1-p'}{1-p}, \quad \text{where} \quad p' = \frac{Q(R)}{R} \cdot p$$

where p is the actual LPS probability and p' denotes the approximation of the probability p due to the quantization Q(R) of the LPS related value of interval width $R=R_{LPS}$. However, instead of evaluating the absolute values of excess codelength D(p,p'), a more meaningful measure is obtained by computing the inefficiency D(p,p') relative to the entropy H(p) (as the average ideal codelength):

$$\delta(p,p') = \frac{D(p,p')}{H(p)}, \quad \text{where} \quad H(p) = -p \log_2 p - (1-p) \log_2 (1-p).$$

Under the assumption that the probability p is fixed with values in $P = \{p_0, p_1, \ldots, p_{N-1}\}$, the *worst case relative excess codelength* $\delta_{max}(\kappa) = \max\{\delta(p,p') \mid p \in P, Q(R) \in Q(\kappa)\}$ can be computed for different choices of κ. It turns out that for κ = 1, δ_{max} is equal to 0.047, whereas $\delta_{max}(\kappa = 2) < 0.013$ and $\delta_{max}(\kappa) < 0.003$ for $\kappa \geq 3$. These values, however, represent the largest relative increase in codelength that can be expected for the largest possible quantization error given by sup |R – Q(R)|.



To calculate the *average relative excess codelength* $\delta_{avg}(p,p') = E[\delta(p,p')]$, a distribution must be assumed for R. Empirically, an 1 / R distribution has been determined for typical sequences of symbols to encode, and based on this empirical distribution the average relative excess codelength δ_{avg} has been computed for each fixed probability state. As shown in the

interval subdivision is practically negligible, at least in case of a static probability distribution and for the choice of $\kappa \geq 2$. By the same kind of analysis it can be shown that the average relative excess codelength resulting from a discretization of the probability space is also negligible (less than 0.05% of the ideal codelength for N = 64).

Related publications:

D. Marpe, H. Schwarz, and T. Wiegand: **Context-Based Adaptive Binary Arithmetic Coding in the H.264 / AVC Video Compression Standard**, *IEEE Transactions on Circuits and Systems for Video Technology*, Vol. 13, No. 7, pp. 620-636, July 2003, ***invited paper.*** **[PDF]**

Errata: On p. 631, left column below Table VI, "max(...)" must be replaced by "min(...)" in the two expressions for specifying context index increments for bins related to absolute values of transform coefficients.

D. Marpe and T. Wiegand: **A Highly Efficient Multiplication-Free Binary Arithmetic Coder and Its Application in Video Coding**, *Proc. IEEE International Conference on Image Processing (ICIP 2003)*, Barcelona, Spain, Sept. 2003. **[PDF]**

D. Marpe, G. Marten, H. L. Cycon: **A Fast Renormalization Technique for H.264/MPEG4-AVC Arithmetic Coding**, *Proc. 51st Internationales Wissenschaftliches Kolloquium* (IWK), Ilmenau University of Technology, Ilmenau, Germany, September 11-15, 2006. **[PDF]**

Related standard contributions (in chronological order, as listed **here**):

[JVT-C061], [JVT-F040], [JVT-U084]

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