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MATLAB-Based 4×4 Block HEVC Intra- Prediction: A Comparative Study

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Abstract: this study assesses an original lossless intra-frame prediction method created in MATLAB for use with the High-Efficiency Video Coding (HEVC) framework. This method was compared with two conventional HEVC image compression standards: the main still picture (MSP) and high range extensions (RExt) standards. The proposed method employs 4×4 block division and incorporates 33 directional prediction modes in addition to planar and DC modes to improve prediction precision through the sum of absolute errors (SAE) measure. Performance evaluation utilized high-resolution images (3264×2448 pixels) sourced from the advanced center of technology (ACT) database, with quality assessment conducted using measures including Peak signal-to-noise ratio (PSNR), structural similarity index (SSIM), and SAE. The proposed method demonstrated competitive results, surpassing the RExt standard in all evaluations. Nevertheless, the HEVC-MSP 16.9 standard yielded superior results, achieving PSNR values of up to 42 dB and reduced SAE measurements, reflecting greater error minimization effectiveness. Although HEVC-MSP outperforms the proposed method in terms of performance, the latter exhibits significant promise for high-resolution image compression applications. Subsequent enhancements may further optimize the effectiveness of the proposed method and broaden its utility across diverse image compression frameworks.

Keywords: Image &Video coding, High-Efficiency Video Coding (HEVC), Intra Prediction coding, HM reference software, Still Image Compression, Lossy & Lossless Compression.

1- Introduction:

The exponential growth of multimedia technologies in recent decades has created substantial requirements for advanced compression techniques to efficiently process image and video data. The proliferation of ultra-high- definition (UHD) and 8K video formats has necessitated considerable improvements in bandwidth utilization and storage solutions [1, 2, 3, 4, 5, 6]. In response to these emerging challenges, the ITU-T Video Coding Experts Group (VCEG) and ISO/IEC Moving Picture Experts Group (MPEG) formed the Joint Collaborative Team on Video Coding (JCT-VC) in 2010 to create the High-Efficiency Video Coding (HEVC) standard, alternatively known as H.265. By 2013, HEVC demonstrated a doubling of compression performance relative to the earlier H.264/AVC standard while preserving equivalent visual quality [2, 3]. As the most efficient breakthrough in digital video compression technology, HEVC employs a hybrid methodology that merges motion-compensation techniques with block-based transform coding. The architecture encompasses both spatial and temporal prediction mechanisms, along with transform processing, quantization, and entropy coding. Compared with H.264/AVC, HEVC delivers approximately double the compression performance at equivalent perceptual quality levels, although this comes at the expense of increased computational requirements [2, 3, 7]. The impetus for HEVC's creation stemmed from the need to overcome constraints inherent in earlier video coding technologies, especially concerning compression performance and high-resolution video support.

HEVC's superior compression capabilities result from multiple sophisticated coding innovations, including support for two data partition structures (slices and tiles) that enable independent decoding and facilitate resynchronization following data loss, implementation of a quad-tree architecture for coding units (CUs) with dimensions spanning 8×8 to 64×64 pixels, expanded intra-prediction capabilities, and refined motion estimation and compensation algorithms [5, 2, 3]. These compression

improvements aree especially valuable for video streaming scenarios where bandwidth limitations and high-quality delivery requirements are paramount concerns [1, 2, 5]. Beyond compression performance, HEVC accommodates resolutions reaching 8K UHD and has been engineered to serve diverse applications such as broadcast television, video-on-demand services, and real-time video conferencing [5, 8, 1]. The standard's adaptability and scalability have established it as a widely adopted solution for both consumer and professional video applications, spanning mobile platforms to sophisticated video production environments [1] [5]. However, The implementation of HEVC faces notable obstacles, particularly regarding computational demands. The encoding procedures in HEVC exhibit substantially greater complexity than those in H.264/AVC, primarily because of the deployment of more sophisticated coding mechanisms and an expanded array of potential coding configurations [7, 4, 3]. This heightened complexity poses difficulties for real-time encoding of high-resolution content, especially on devices with limited processing capabilities.

HEVC utilizes two fundamental prediction methodologies: intra-prediction, which derives block content estimates from spatial data within neighboring blocks of the same frame (predominantly applied in I-frames and static images), and inter-prediction, which exploits temporal redundancies by referencing information from preceding or subsequent frames (employed in P- and B-frames) to improve compression performance [1, 2, 3, 4, 5, 6]. Intra-prediction is an essential element of HEVC which estimates block content using spatial information derived from adjacent blocks within an identical frame.

The intra-prediction process in HEVC operates through two distinct phases: determining prediction unit (PU) dimensions and selecting prediction modes [3, 2]. HEVC provides 35 distinct intra-prediction modes, representing a significant expansion from the 11 modes offered by H.264/AVC, accompanied by adaptable block size partitioning from 4×4 to 64×64 samples, thereby reducing intra-prediction residual errors and facilitating more accurate representation of directional patterns.

The HEVC standard accommodates both lossless and lossy compression methods. Lossless compression maintains complete fidelity to the original content without any information loss, whereas lossy compression achieves reduced file sizes by eliminating less critical data, thereby creating a balance between file dimensions and visual fidelity [9, 10]. Particularly, lossless intra-compression reduces prediction errors, yielding enhanced image precision.

The HEVC-HM Test Model Encoder functions as the reference implementation, offering support for multiple profiles including Main, Main 10, MSP, and RExt, thereby enabling extensive applicability across varied scenarios [6, 11]. The continued advancement of HEVC has resulted in the development of various extensions and profiles, notably RExt and MSP extensions, which augment the standard's functionality for specialized applications. These extensions deliver support for increased bit depths, expanded color gamut, and lossless encoding capabilities, establishing HEVC as a flexible standard suitable for numerous applications including professional video production, medical imaging, and screen content encoding [4, 9].

Multiple research efforts have investigated optimization strategies for HEVC intra-prediction, concentrating on performance metrics such as SAE, rate-distortion optimization (RDO), and hybrid methodologies that integrate these metrics to achieve enhanced coding performance [12, 13].

The present study conducts a comprehensive analysis of the lossless intra-prediction process for 4×4 blocks in HEVC using MATLAB implementation. The research assesses SAE-based prediction results in comparison with established HEVC benchmarks, emphasizing two practical compression profiles—MSP and RExt—utilizing the HM 16.9 encoder version. The evaluation was performed using the ACT image database (3264 × 2448 pixels) from the materials science department at the ACT in Tripoli to determine the efficacy of the proposed methodology.

2- HEVC INTRA-PREDICTION CODING

HEVC standard has made significant strides compared to its predecessor, H.264/AVC, enabling it to double the compression ratio while preserving visual quality. A key advancement in HEVC is its ability to support a broad spectrum of block sizes, ranging from 64 x 64 to 8 x 8 samples allows HEVC to effectively encode diverse video content with high accuracy. HEVC also, expands the number of intra-prediction modes to 35, a substantial increase from the 11 modes in H.264/AVC: 33 angular modes, a planar prediction mode, and a DC prediction mode [3, 14]. This enhancement improves the HEVC's capacity to capture various directional patterns, including horizontal, vertical, and diagonal edges commonly observed in natural images and videos columns for the current block.

The implementation of angular intra-prediction in HEVC has considerable implications for numerous multimedia applications, such as video streaming services, video conferencing, virtual reality (VR), and augmented reality (AR), where efficient compression is crucial for maintaining high visual quality while minimizing bandwidth requirements. The enhanced compression efficiency achieved through angular prediction results in decreased storage and bandwidth needs, which is essential for effective content delivery via the internet and other digital platforms [2]. HEVC intra-frame prediction based on determining pixel values according to the pixels in adjacent blocks in same frame, which function as the reference row or column for the current block. A set of 35 intra-prediction modes is available in HEVC with varied block sizes, including a DC (Mode-1), a Planar (Mode-0), and 33 Angular (Mode-2…34) Modes for all the block sizes, as illustrated in table-1.

Table 1. Hevc Intra Prediction Modes Supported For Different PU Sizes [15, 16].

Size of PU	Number of Intra Prediction	Intra-Prediction Modes
4x4	18	0-16, 34
8x8	35	0-34
16x16	35	0-34
32x32	35	0-34
64x64	4	0-2, 34

In intra mode, Coding Units (CUs) are predicted using reconstructed neighboring samples located at the top and left of the Prediction block within the same slice. This is particularly the case for I slices, where only intra prediction is enabled. For P and B slices, CUs can either be in the intra- or inter-prediction mode. When the current Prediction Unit (PU) has a size of N×N, a total of 4N+1 spatially neighboring samples from previously decoded boundary samples are utilized.

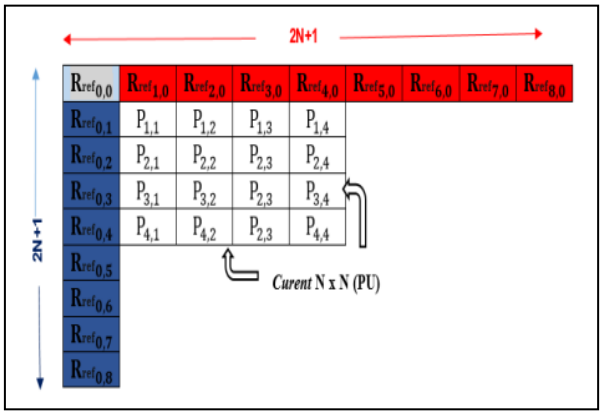


Fig. 1 Reference sample for a block of size N × N samples.

All sample locations within one prediction block are projected to a single reference row or column, depending on the angular mode as shown in Fig. 1. It is clear that all sample locations within one prediction block are projected to a single reference row (depicted as red samples) for angular modes 18-34 or a column (depicted as blue samples) for angular modes 2-17. The intra-prediction process is performed by extrapolating samples from the reconstructed reference samples, utilizing a given directionality along the horizontal and vertical directions, depending on the displacement angularity parameter A. The 33 displacement angularity parameters were categorized into vertical and horizontal angular predictions, each with negative and positive angles, as illustrated in [3].

For example: Prediction modes 2, 18, and 34 are performed by sample extrapolation at 45° angles, while modes 10 (vertical) and 26 (horizontal) involve direct extrapolation of samples located in the left and top reconstructed blocks, respectively, as shown in Fig.2.

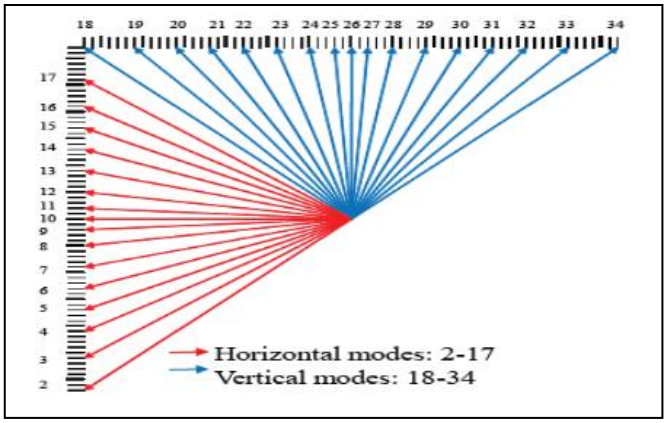


Fig. 2 Angular Intra-Prediction modes in HEVC [10].

The implementation of the 33 angular prediction modes, along with the planar and DC modes in MATLAB, is described below. The following Eq.1 is used to calculate the angular predicted sample P (x, y) using linear interpolation functions of the reference sample related to each mode [15]:

$$P_{x,y} = ((32 - iFact) * a\ R + iFact * b + 16) >> 5 \quad (1)$$

Where;

- x and y are the spatial coordinates.
- $P_{x,y}$ denotes the current predicted sample.
- A is the displacement tangent with a resolution of 1/32, which ranges from −32 to +32.
- iFact is the distance between the two reference samples.
- a and b are the reference samples for the current predicted sample, which are identified by a reference picture index that depends on the intra-prediction angle.
- iFact = (x · A) & 31 horizontal mode & = (y · A) & 31 vertical mode and Index = y+ iFact.
- 32 – iFact = (x· A) >>5 horizontal mode & = (y· A) >>5 for vertical mode, and Index = x+ iFact.
- >> denotes a bit shift operation to the right.
- & denote the logical AND operations.

Planar prediction in HEVC is a multidirectional process that interpolates each PU sample from the right column and bottom line, which is ideal for textured areas, prevents discontinuities, and averages vertical and horizontal interpolations. It was computed using Eq. (4) [15]:

$$P^{H}_{x,y} = (N-x) * R_{y,0} + x * R_{0,N+1} \quad (2)$$

$$P^{V}_{x,y} = (N-y) * R_{0,X} + y * R_{N+1,0} \quad (3)$$

$$P_{x,y} = \text{floor}\ ((P^{V}_{x,y} + P^{H}_{x,y} + 16 / (\log2(N) + 1)) \quad (4)$$

The DC Mode in HEVC is a simple prediction method that uses the average value of the reference samples around the block to predict all pixels within the block, which is computed using Eq. (5).

$$P_{Dc} = \frac{1}{2N}\left(\sum_{x=1}^{N} Rref_{x,0} + \sum_{y=1}^{N} Rref_{0,y}\right) \quad (5)$$

Moreover, continuous improvements in HM test model versions indicate superior compression efficiency. Here, we describe the implementation of the proposed 4 × 4 fixed-block intra-prediction coding algorithm and evaluate its performance in terms of visual quality and error metrics with existing HEVC, after configuring it to work on fixed 4 × 4 prediction blocks. In this study, the proposed algorithm for lossless intra-frame prediction (4 × 4 pixels) block partitioning of HEVC using MATLAB leverages advanced prediction modes by implementing angular, planar, and DC predictions and selecting the optimal prediction mode based on most known error metrics SAE.

3- Description of the proposed method:

Many previous studies have demonstrated the efficacy of HEVC's intra-prediction in still image compression. For instance, an analysis comparing HEVC intra coding with Joint Photographic Experts Group (JPEG) and JPEG 2000 revealed that HEVC achieves an average bit rate reduction ranging from 16% (compared to JPEG 2000 4:4:4) up to 43% (compared to JPEG), indicating superior compression efficiency [17]. Here, we describe the implementation of the proposed 4 × 4 fixed-block

lossless-intra-prediction coding algorithm and evaluate its performance in terms of visual quality and error metrics with existing HEVC, after configuring it to work on fixed 4×4 prediction blocks.

A. Proposal 4 x 4 Hevc Lossless Intra-Prediction Matlab Algorithm:

To achieve our objective, angular intra-prediction, planar and DC predictions, and selection of the optimal prediction mode are based on several steps:

- **a)** Reads an tiff image.
- **b)** Block partitioning: To characterize the texture in the localized image area well, the image component is divided into square blocks fixed to 4×4 blocks to obtain the finest analysis size for all 35 intra-modes.
- **c)** Reference sample construction: A reference sample array is constructed using the original image pixels to serve as predictors for the current block.
- **d)** Prediction mode development: The 33 angular prediction modes, along with the planar and DC modes, were applied in MATLAB.
- **e)** Prediction mode selection: choose the most suitable angular prediction mode based on the content of the block and minimize the residual error for each predicted block.
- **f)** Reconstruction of the predicted image: The frame was reconstructed using the selected prediction modes.
- **g)** Compute the SSIM, SAE, and PSNR for the reconstructed predicted image.

B. Comparison with other existing Lossless Intra-Frame 4 x 4 Prediction HEVC Algorithms:

Here, we propose ensuring efficient and high-quality image compression MSP and RExt profiles using HEVC reference software HM 16.9 with a fixed PU size of 4×4 blocks to enhance their performance and adherence to the HEVC standards. Here, we repeat the same steps starting with converting RGB to YUV Color Space, which focuses on the luma component (Y) for intra prediction, as it contains the most significant information for visual perception, to be an input file for the HEVC-HM 16.9 encoder. The HEVC-HM test model has undergone several version updates, each bringing improvements and new features. The HEVC high-throughput and Main still picture profiles offer advanced features for still-image lossless intra compression. By supporting up to 16-bit depth, these profiles ensure efficient and high-quality image compression. The implementation used HEVC reference software HM 16.9 [11] , with a fixed PU size of 4 x 4 blocks aiming enhances their performance and adherence to the HEVC standard.

In addition, for authentic performance analyzing the Codec Visa software analyzing used for verifying the HM encoder bit stream file.

4- Performance Evauation Results:

We selected three high-resolution images (3264 x 2448 pixels) from the ACT database to compare the performance of the different encoders. The large size and detailed content of these images make them ideal for evaluating the effectiveness of the proposed HEVC lossless intra-prediction method against other encoders. The performance assessment involves three main metrics: PSNR in dB, SSIM, and SAE. Fig. 3 summarizes the results for the three high-resolution lossless predicted images, detailing the residual metrics and the visual quality of the reconstructed predicted image.

Based on the evaluation visual quality metrics presented above, the HM 16.9 HEVC-MSP profile (sub-figure c) generally outperformed the proposed HEVC intra- prediction module in terms of PSNR and SSIM values, particularly for Image 2 and Image 3. This indicates that the HM 16.9 MSP-profile provides slightly better image quality and compression efficiency for these images. Higher PSNR values generally indicate better image quality. The proposed HEVC intra-prediction module (sub-figure b) achieved notable PSNR values, especially for Image 2 (40 dB) and Image 3 (31 dB). However, the HM 16.9 HEVC-MSP (sub-figure c) showed superior PSNR values for Image 2 (42 dB) and Image 3 (32 dB), suggesting slightly better compression efficiency for certain images. The proposed HEVC intra prediction module achieved high SSIM values, particularly for Image 2 (0.96) and Image 3 (0.92).

The HM 16.9 HEVC-MSP profile displayed even higher SSIM values for Image-2 (0.97) and Image-3 (0.93), highlighting superior performance in maintaining structural integrity. Additionally, the SAE values indicate lower prediction errors for the HM 16.9 HEVC-MSP (sub-figure c) than for the proposed HEVC intra prediction module. For example, Image-2 shows an SAE of 10.6 x 10^6 for the

HM 16.9 profile versus 13 x 10^6 for the proposed module, demonstrating the superior efficiency of the HM 16.9 profile in minimizing errors. However, the proposed HEVC Lossless intra-prediction module also demonstrated competitive performance, achieving high-quality results across all three images.

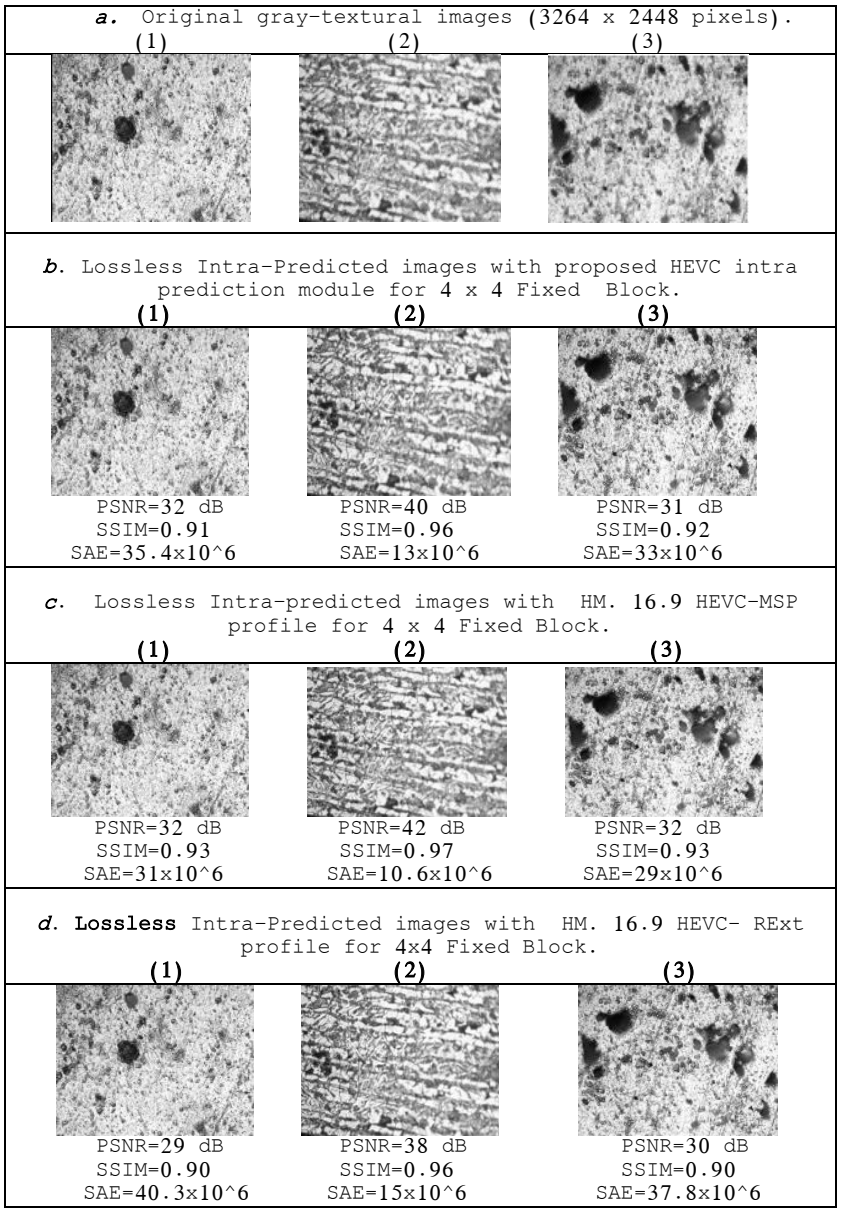


Fig. 3 Illustrates the effectiveness of the proposed three HEVC intra-prediction processes to predict three original images (Resolution of 3264 x 2448 pixels).

These findings provide robust evidence for the effectiveness of both the proposed HEVC lossless intra-prediction method and the HM 16.9 HEVC-MSP in achieving high-quality video compression and efficient performance. Overall, while the HM 16.9 HEVC-MSP profile generally outperformed the proposed HEVC intra-prediction module, both methods demonstrated their capability to achieve high visual quality and efficient compression, making them suitable for various high-resolution image compression applications.

5- Conclusion

This study presents an in-depth analysis of HEVC's lossless intra-prediction process for 4×4 blocks, focusing on SAE-based optimization implemented in MATLAB. The results demonstrate that the proposed algorithm can achieve efficient lossless compression with competitive image quality, as indicated by PSNR and SSIM metrics. Although the HM 16.9 HEVC-MSP profile generally yielded superior results, particularly images, the proposed method demonstrated notable performance in

specific scenarios, highlighting its potential for further optimization. The flexibility and precision of HEVC's 35 intra-prediction modes play a critical role in enhancing the compression efficiency, particularly for high-resolution images. Future research should explore additional optimization strategies to reduce computational complexity and improve real-time encoding capabilities, making the method more viable for practical applications across various multimedia platforms.

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