JPEG AI Standard: Learning an Efficient and Rich Visual Data Representation

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Outline

1. Context and Motivation
2. The JPEG AI Project
3. JPEG AI Verification Model
4. Performance Evaluation
5. Going Forward ...
Context and Motivation
Rich Ecosystem of Image Technologies
Image Compression Landscape

JPEG

GIF
PNG

HEVC

JPEG2000

AV1
H.266

webp
Classical Image Compression Pipeline

JPEG: simple, elegant, large ecosystem, interpretable, ...

Original

Quality Metric

Decoded

Linear Hand-crafted Transform

Quantization

Entropy Coding

Bitstream

Quantization Levels

Entropy Coding Model

Entropy Decoding

Bitstream
Deep Learning Explosion!

Giga Floating-point Operations Per Second that you can buy with 1 USD

1. Big Data
   - Larger Datasets
   - Easier
   - Collection & Storage

2. Hardware
   - Graphics Processing Units (GPUs)
   - Massively Parallelizable

3. Software
   - Improved Techniques
   - New Models
   - Toolboxes
Deep Learning Achievements: Computer Vision

- Extremely successful in computer vision tasks:
  - Image classification, object detection, semantic segmentation, ...
  - Face recognition, image generation, video understanding, ...

![Image Classification Examples]

- Easiest classes:
  - Red fox (100)
  - Hen-of-the-woods (100)
  - Ibis (100)
  - Goldfinch (100)
  - Flat-coated retriever (100)

- Hardest classes:
  - Muzzle (71)
  - Hatchet (68)
  - Water bottle (68)
  - Velvet (68)
  - Loupe (66)


Deep Learning Achievements: Image Processing

- Extremely successful in image processing tasks:
  - Denoising, super-resolution, inpainting, style transfer, segmentation, ...
  - Many other image restoration tasks (dehazing, deraining, etc.), ...

![Image of a person and artistic images]
Visual Coding vs Neural Networks

- Learning-based image compression
  ✓ Non-linear transformations, entropy coding models, etc.

- Learning-based video compression
  ✓ Optical flow, motion compensation, multi-frame fusion, etc.

- Models for typical image/video compression modules
  ✓ Intra-prediction, in/out loop-filtering, entire encoder, etc.

- Learning-based point cloud compression
  ✓ Geometry and attribute compression methods, etc.

- Learning-based light-field compression
  ✓ Stereoscopic and multi-view representations, NeRF, etc.

- Neural networks models and activations compression
  ✓ Enabling the efficient transmission of large models (or activations)
Image Compression with Neural Networks

- Very recent and promising field

As old as JPEG !!!
2
The JPEG AI Project
JPEG AI Project

- JPEG AI Project (ISO/IEC 6048) aims to develop and standardize learning-based image compression
  - Joint standardization effort between SC29/WG1 and ITU-T SG16
  - Call for Proposals has been issued and all submissions evaluated
  - Collaborative phase has started towards the definition of a verification model

- Many industry and academia involvement!
The JPEG AI scope is the creation of a learning-based image coding standard offering a single-stream, compact, compressed domain representation, targeting both human visualization, with significant compression efficiency improvement over image coding standards in common use at equivalent subjective quality, as well as effective performance for image processing and computer vision tasks, with the goal of supporting a royalty-free baseline.

<table>
<thead>
<tr>
<th>Image processing tasks</th>
<th>Computer vision tasks</th>
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<tr>
<td>Super-resolution</td>
<td>Image retrieval and classification</td>
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<td>Low-light enhancement</td>
<td>Object detection and recognition</td>
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<td>Exposure compensation</td>
<td>Event detection and action recognition</td>
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<td>Inpainting</td>
<td>Face detection and recognition</td>
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Advantages for image processing and computer vision task:

- **Single-stream representation**: same compressed stream is also useful for decoding
- **Energy efficient**: reduces the resources needed to perform these tasks
- **High accuracy**: allows performing these tasks using features extracted from the original instead of the lossy decoded images
Application-driven Requirements

- High coding efficiency is important for many applications such as cloud storage or media distribution

- Content understanding is vital for many applications such as visual surveillance, autonomous vehicles, image collection management, etc
  - Objects may need to be recognized
  - Images may need to be classified for organization purposes
  - Actions or events may need to be recognized

- Content is not consumed by humans in the same way as the original reference in many applications such as in media distribution
  - Noise can be reduced
  - Resolution can be increased
  - Colors can be corrected
3

JPEG AI Verification Model
JPEG AI VM High Level Architecture

- New architecture never proposed before
  - Works with YUV colour space and supports 4:4:4 and 4:2:0
  - Exploits spatial correlation with the analysis and synthesis transforms
  - Probabilistic latent model is obtained from side information (hyper-prior)

- Two encoding pipelines are present, one for luma and another for chroma
  - Chroma pipeline encodes UV in half of the resolution of Y (and has less depth)
  - Independent pipelines using networks with same architecture, but different number of channels
Probability table for entropy coding is modelled with \( \mathbb{N}(0,\sigma) \) for every latent element.

Latents are predicted and only the residual is coded and transmitted.
- Exploits spatial correlation at the latent domain.

Entropy decoding is decoupled of latent prediction and reconstruction.
- Entropy decoding of a latent doesn’t depend on previously decoded latents.

Hyper scale decoder
- Provides estimation of the variance of the entropy coding model distribution.

Hyper "mean" decoder
- Provides estimation of the mean (explicit prediction) of the latent.
JPEG AI VM Encoder Architecture

- Analysis Transform
- Hyper Encoder
  - Scaling and Rounding
  - Entropy Encoder (me-tANS)
- Entropy Decoder (me-tANS)
- Bitstream
- Hyper-scale Decoder
- Hyper-mean Decoder
- Latent Prediction (MCM)

**Key Terms**
- me-tANS: memory efficient tabular Asymmetric Numeral Systems
- MCM: multistage context model
JPEG AI VM Decoder Architecture

Synthesis Transform

Bitstream

Entropy Decoder (me-tANS)

Hyper-scale Decoder

Hyper-mean Decoder

Latent Prediction (MCM)

NN layers

classical
Addressing Complexity Issues

- Three operating points are supported:
  - CPU operating point targeting legacy devices
  - Base operating point targeting mobile devices
  - High operating point for more hardware-capable devices with powerful GPUs and no energy constraints

- Base operating point should provide 10-15% compression efficiency gains over VVC Intra with approx. 22 kMAC/px

- High operating point should provide 25-30% compression efficiency gains over VVC Intra with approx. 220 kMAC/pxl
JPEG AI Multi-branch Decoding

Receiver can support just one decoder (operating point) to decode any stream

JPEG AI VM supports

2 Encoder x 3 Decoder = 6 possible combinations compatible to each other
JPEG AI has a LOT of flag-enabled Tools

- Skip mode allows skip writing/parsing from the bitstream residual latent elements which can be identified by encoder and decoder to be zero
- Variable rate coding with Gain Units
  - Model parameters defined by ModelID
  - “Gain” factor for residual & variance defined by $\Delta \beta$ (signalled)
- Residual and the standard deviation parameter scaling
- Enhancement filters increase mostly the chroma quality
Tool Example: Enhancement Filter Technologies

- Enhancement filters bring 26% gain in Chroma PSNR
- Linear chroma filter and non-linear chroma filter use signalled parameters and perform upsampling/color correction
- Inter channel correlation information filter provides enhancement of colour information exploiting correlation with luminance
- Luma edge filters adaptively enhances (scale) edges to improve decoded quality
Device Reproducibility

Due to the use of floating-point arithmetic and different orders for the operations the result depends on platform heavily.

Leads to wrong interpretation of the parsed symbols in arithmetic coder.

How does effect look like?

Encoded and decoded on same device

Encoded and decoded on different devices
The tensor $\text{weight}$ of shape $[C_{in}, C_{out}, K_{ver}, K_{hor}]$ contains learnable 8-bit integer weights, the tensor $\text{bias}$ of shape $[C_{out}]$ contains learnable 31-bit integer biases. All parameters $\text{weight}$ and $\text{bias}$ are part of learnable quantized model.

The combination of clipping value $d$, de-scaling shifts $p[C_{out}]$ and magnitude for the quantized model parameters allows control over bit depth of register $R[C_{out}, i, j]$ (guaranteed to be within 32 bits).
Spatial Prediction @ Latent Domain

- Aims to predict the mean of $\tilde{y}$ using the explicit prediction and residual decoded data
  - 3D chess-board split of the tensor

- Significant complexity reduction (minimizes serial processing) in comparison to previous approaches such as wavefront parallelizable models with masked convolutions

Data Compression Conference
Multistage (4-stage) Context Model

- Hyper-mean encoder provides an explicit prediction derived from the hyper latent tensor
- 4-stage context model: concatenates and process already reconstructed latent sample groups which are fused together with the explicit prediction of the hyper mean decoder
**Synthesis Transform**

High Operation Point ~180 kMAC/pxl

Base Operation Point ~20 kMAC/pxl

Network is deeper for primary component (Luma)

Figure 8.3.1 – Synthesis transform Net
Bring the Attention!

Attention modules only for High profile

**TAM**

Transformers-based Attention Module

**CAB**

Convolutions-based Attention Block

Figure 8.3-1 – Synthesis transform Net
Attention Blocks: Convolutional vs Transformer

Three branches to represent skip, feature and mask (to improve receptive field)

Three branches to represent query, key and value
Transposed-attention map A of size $C \times C$ is computed

Figure 3.5.30-1 - Convolution-base attention block

Figure 3.5.39-1 Transformer-based attention block.
JPEG AI Region of Interest Decoding

The residual is multiplied by a gain tensor for local quality control. Quality index map is predicted, coded and inserted into the codestream.

- JPEG AI VM3.4 - 0.12 bpp
- JPEG AI VM3.4 + ROI coding - 0.10 bpp

Original image
ROI mask (white)

Allocating more bits on the ROI and fewer bits on the background.
JPEG AI Progressive Decoding

Partial decode part of the 160 channels of residual can reduce the time used for decoding.

SOP-Luma-0-Chroma-16 (9.3% of the bit-stream)

SOP-Luma-1-Chroma-16 (11% of the bit-stream)

SOP-Luma-2-Chroma-16 (12% of the bit-stream)

SOP-Luma-4-Chroma-16 (14% of the bit-stream)

SOP-Luma-8-Chroma-16 (18% of the bit-stream)

SOP-Luma-16-Chroma-16 (25% of the bit-stream)
Performance Evaluation
JPEG AI Dataset

JPEG AI Test Set:
50 camera captured images

Training Set:
5000+ images

Validation Set:
350+ images
JPEG AI Additional Datasets

36 synthetic images

12 HDR images
JPEG AI RD Performance

tools-off: only “off-line trained”, no content adaptation, no encoder search,
## JPEG AI VM4 RD Performance

### Base operating point!

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**Legend:**
- **RVS** – Residual and Variance Scale
- **Filters** – Adaptive re-sampler, ICCI (cross-color filter), LEF (luma edge filter) and non-linear chroma filter
- **LSBS** – Latent Scale Before Synthesis
- **CWG** – Channel-Wise Gain
# Performance with Multi-branch Decoding

Only differ in the analysis and synthesis transforms
- Enc0 – Synthesis Transform without attention
- Enc1 – Synthesis Transform with attention
- SOP – Simple operating point
- BOP – Base operating point
- HOP – High operating point

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For the CPU platform, the decoder complexity is 1.6x/3.1x times higher compared to VVC Intra (reference implementation) for the simplest/base operating point.
VVC 0.50 bpp
VMAF = 80.3 PSNR-Y 31.4 MS_SSIM = 0.987

VM3.4-HOP-tools-on 0.44 bpp
VMAF=88.07 PSNR-Y=30.6 MS_SSIM = 0.992

Original
JPEG AI Decoder on Smartphones

Main targets:

- Demonstrate to the world that JPEG AI can fly on smartphone right now even without dedicated chip
- Identify JPEG AI design issues preventing deployment on mobile platform as early as possible
- Verify device interoperability of JPEG AI standard

- **Configuration**: JPEG AI CE6.1/VM3.4 base operating point
- **Device #1**: Huawei Mate50 Pro with Qualcomm Snapdragon 8+ Gen1
- **Device #2**: iPhone 14/15 Pro Max, 1K patch images
JPEG AI Smartphone Demos

Huawei Mate50 Pro

Iphone 14 Pro Max
Going Forward …
Biological Inspired Acquisition

Deep learning already disrupted compression! What about sensing?

Differential visual sampling model in which time-domain changes in the incoming light intensity are pixel-wise detected and compared to a threshold, triggering an event if it exceeds the threshold.
Event-based or Neuromorphic Imaging

- Event cameras each sensor pixel is in charge of controlling the light acquisition process in an asynchronous and independent way
  - According to the dynamics of the visual scene
  - Producing a variable data rate output

- Relevant advantages:
  - High temporal resolution
  - Very high dynamic range
  - Low latency
  - Low power consumption
  - No fixed frame rate
New Exploration Activity!

The scope of JPEG XE is the creation and development of a standard to represent Events in an efficient way allowing interoperability between sensing, storage, and processing, targeting machine vision applications.
JPEG AI Next Steps

- Profile/level and conformance discussion has started and is ongoing
- Version 1 addresses several (but not all) JPEG AI ‘core’ and ‘desirable’ requirements with emphasis on compression efficiency for standard reconstruction
- Version 2 will address/include:
  - JPEG AI requirements not yet addressed in version 1, e.g. related to processing and computer vision tasks
  - Significantly improved solutions for JPEG AI requirements already addressed in Version 1, e.g. compression efficiency

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Final Remarks

- The first learning-based image compression international standard is under active development!
  - Significant higher compression efficiency compared to the best performing conventional image coding solutions, notably H.266/VVC and H.265/HEVC
  - Can be efficiently deployed in resource-constrained mobile devices
  - Much less encoding complexity, online encoder search is now done offline

- Main challenge is to have a multi-purpose bitstream (THE visual language) that is good for a multitude of visual tasks!
  - Not only image compression but for content understanding and image enhancement!

- “Artificial Intelligence” can be brought to the sensing process to have an even more rich visual data representation!
Thank you for your hard work and dedication!