Impact of Substitution Noise on Transform-Based Image Codecs for DNA Storage

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One of the main challenges in DNA data storage is optimizing the performance of the encoder in presence of biochemical errors. Indeed, the synthesis and sequencing of the DNA strands are processes prone to errors that need to be corrected. Recently, the JPEG committee created a project called JPEG DNA (ISO/IEC 25508) with the goal of standardizing for the first time an image compression process for DNA storage. The elected pipeline is described in Figure 1 with first a binary compression (JPEG XL) then a quaternary one (DNA Raptor).

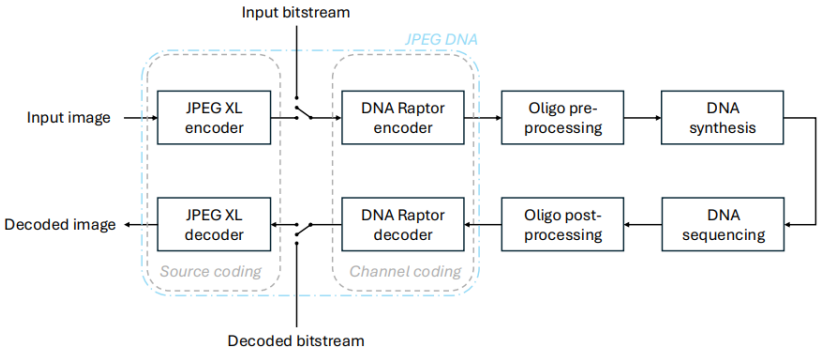


Figure 1: Image coding workflow with JPEG DNA [1].

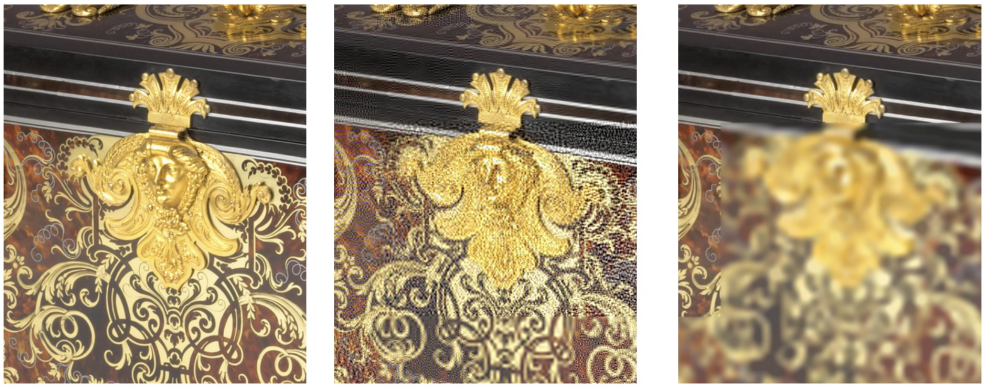
The objective of this work is to study the impact of substitution noise on image decoding in DNA storage pipelines. In practical DNA storage systems, the assumption of perfect error correction is unrealistic, as synthesis and sequencing processes introduce errors such as substitutions, insertions, and deletions. Understanding how these errors propagate through the decoding pipeline is crucial to evaluate the robustness of image compression methods in realistic noisy conditions.

We focus on transform-based image codecs, in particular JPEG XL, which serves as our reference decoder. More generally, we restrict our study to mature non learning-based compression methods, including error resilient versions of JPEG XL and JPEG 2000. This choice is motivated by their well-understood structure, controlled computational complexity, and, most importantly, their more predictable behavior in noisy end-to-end systems such as DNA storage pipelines. In contrast, learning-based codecs are not considered here: although they may achieve higher reconstruction quality under perfect error correction [2], their limited resilience to errors makes them unsuitable for a fair evaluation in noisy scenarios.

In our experiments, substitution errors are introduced at the FASTA level after quaternary encoding (Raptor) and quantified as a percentage of the total number of oligos. These substitutions can propagate through the decoding pipeline, potentially causing failures at both quaternary and binary decoding stages.

The evaluation assesses both decoding success rate and visual quality of the reconstructed images. By comparing JPEG XL and JPEG 2000 under identical noise conditions, we analyze how

codec design influences robustness to substitution errors and the resulting perceptual degradation. Preliminary results are shown in figure 2.



(a) Original (b) JPEG 2000 (c) JPEG XL

Figure 2: Image 00001 of AIC-3 dataset [3] - 0.01% substitution errors - Visual impact of the noise without error correction.

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References

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