# Robust3DGSW: Toward Robust Watermarking for Quantization-Aware 3D Gaussian Splatting

## Supplementary Material

## A. Ablation Study

### A.1. Ablation on Frequency Band Selection

To validate our design choice of mid-frequency band embedding, we compared various frequency band selections for watermark embedding in the 3D Gaussian position domain. Table 2 shows the results using 4-bit quantization.

Table 2. Ablation study on frequency band selection for 3D Gaussian watermark embedding under 4-bit quantization.

| Band | PSNR(dB) | SSIM | LPIPS | Acc(%) |
|---|---|---|---|---|
| Low-frequency [0, 1/8] | 14.82 | 0.73 | 0.28 | 69.74 |
| High-frequency [3/8, 1/2] | 18.27 | 0.82 | 0.19 | 56.32 |
| Full-frequency [0, 1/2] | 13.95 | 0.71 | 0.31 | 71.85 |
| **Mid-frequency [1/8, 3/8]** | **20.46** | **0.88** | **0.12** | **87.51** |

As indicated in Table 2, the mid-frequency band offers an optimal balance between rendering quality and watermark robustness. Low-frequency embedding alters DC components and coarse structures, leading to significant visual distortions (PSNR: 14.82 dB) that negatively impact perceptual quality. In contrast, high-frequency embedding achieves better image quality (PSNR of 18.27 dB) but struggles with weak watermark extraction (accuracy of 56.32%), primarily due to 4-bit quantization, which often eliminates high-frequency information through rounding errors. Full-frequency embedding combines the drawbacks of both low- and high-frequency approaches, resulting in the lowest PSNR of 13.95 dB. In comparison, our selection of mid-frequency band embedding effectively addresses quantization-induced signal loss and reduces the negative effects of watermarks on rendered images. This confirms the validity of our choice of the frequency-band watermark embedding method, as discussed in Section 3.2.

### A.2. Ablation on embedding hyperparameters

Table 3. Ablation study on watermark embedding hyperparameters under 4-bit quantization.

| $\alpha_{3D}$ / $\alpha_{2D}$ | PSNR(dB) | SSIM | LPIPS | Acc(%) |
|---|---|---|---|---|
| 0.5 / 0.5 | 24.53 | 0.93 | 0.07 | 72.18 |
| 0.75 / 0.75 | 22.41 | 0.91 | 0.09 | 81.34 |
| **1.0 / 1.0 (Default)** | **20.46** | **0.88** | **0.12** | **87.51** |
| 1.5 / 1.5 | 16.23 | 0.82 | 0.19 | 91.27 |
| 2.0 / 2.0 | 12.84 | 0.74 | 0.28 | 93.42 |

We investigated how the hyperparameters for watermark embedding affect the trade-off between image quality and watermark extraction accuracy. We follow the setup described in [9], where we set $\alpha_{3D} = \alpha_{2D}$. Table 3 presents the results for 4-bit quantization with varying hyperparameter values. When $\alpha_{3D} = \alpha_{2D} = 0.5$, the Peak Signal-to-Noise Ratio (PSNR) is 24.53 dB, which indicates good rendering quality. However, the weak watermark embedding in this configuration leads to an extraction accuracy of only 72.18%. In contrast, setting $\alpha_{3D} = \alpha_{2D} = 2.0$ increases extraction accuracy to 93.42%, but at a cost: visual quality deteriorates greatly, yielding a PSNR of just 12.84 dB.

### A.3. Performance under Quantization

To evaluate the effectiveness of Robust3DGSW at different quantization levels, we also assessed its performance with 16-bit and 8-bit quantization. As shown in Tables 4 and 5, Robust3DGSW consistently demonstrates superior performance, underscoring its robustness.

Table 4. Performance comparison (with 16-bit quantization).

| Methods | No Distortion | | | | Distortions (Bit Accuracy %) | | | |
|---|---|---|---|---|---|---|---|---|
| | PSNR(dB) | SSIM | LPIPS | Acc(%) | Noise | Blur | Rotation | Crop |
| GaussianMarker | 29.18 | 0.893 | 0.108 | 85.71 | 84.83 | 83.45 | 84.63 | 80.28 |
| 3D-GSW | 30.52 | 0.865 | 0.113 | 82.36 | 81.94 | 80.74 | 83.18 | 81.35 |
| StegaNeRF+3DGS | 28.64 | 0.851 | 0.119 | 88.80 | 51.73 | 71.82 | 63.19 | 70.46 |
| HiDDeN+3DGS | 27.32 | 0.847 | 0.154 | 48.65 | 47.31 | 47.54 | 46.79 | 45.86 |
| **Robust3DGSW (Ours)** | **34.67** | **0.945** | **0.094** | **92.48** | **87.27** | **87.18** | **87.43** | **88.06** |

Table 5. Performance comparison (with 8-bit quantization).

| Methods | No Distortion | | | | Distortions (Bit Accuracy %) | | | |
|---|---|---|---|---|---|---|---|---|
| | PSNR(dB) | SSIM | LPIPS | Acc(%) | Noise | Blur | Rotation | Crop |
| GaussianMarker | 20.64 | 0.841 | 0.211 | 75.84 | 71.93 | 69.27 | 67.15 | 68.42 |
| 3D-GSW | 21.64 | 0.855 | 0.190 | 77.90 | 66.14 | 70.83 | 67.59 | 69.76 |
| StegaNeRF+3DGS | 17.32 | 0.724 | 0.297 | 73.22 | 46.85 | 59.17 | 55.94 | 60.23 |
| HiDDeN+3DGS | 16.24 | 0.716 | 0.348 | 46.52 | 45.87 | 45.28 | 45.73 | 45.94 |
| **Robust3DGSW (Ours)** | **34.32** | **0.924** | **0.095** | **89.36** | **81.63** | **81.48** | **82.79** | **84.14** |

At 16-bit quantization, the performance of some baseline methods remains satisfactory. Notably, Robust3DGSW achieves a watermark extraction accuracy of 92.48% and a PSNR of 34.32 dB, outperforming all baseline methods. However, with 8-bit quantization, the baseline methods experience a significant decline in performance, whereas Robust3DGSW maintains strong results, with only a 3.12% drop in accuracy relative to 16-bit quantization. Even with 8-bit quantization and geometric distortion, Robust3DGSW achieves over 80% accuracy across all distortion types, performing particularly well with crop distortion, reaching 84.14%.

The baseline methods exhibit critical weaknesses: i) **GaussianMarker**: The spatial-domain watermarks are directly affected by rounding errors caused by quantization. ii) **3D-GSW**: High-frequency embeddings are preferentially removed at 8-bit precision. iii) **StegaNeRF+3DGS** and **HiDDeN+3DGS**: These methods, designed for full-precision NeRF models, do not incorporate quantization-aware optimization, resulting in failures under sub-8-bit quantization.