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ADAPTIVE LSB: DWT–DCT AND QIM BASED WATERMARKING: A SCALABLE APPROACH TO IMPERCEPTIBLE AND ROBUST VIDEO SECURITY

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ABSTRACT
Digital multimedia systems increasingly demand secure and imperceptible embedding of data within any digital content, especially in applications such as copyright protection, content authentication, and multimedia forensics. Traditional watermarking techniques often depend solely on spatial- or frequency-domain techniques, achieving robustness against various video-processing operations. This paper proposes a hybrid watermarking framework that embeds audio payloads into video frames using a dual-domain strategy combining Least Significant Bit (LSB) spatial embedding and mid-band DWT–DCT frequency embedding in (1:3) ratio. The approach integrates payload chunking, error-correcting codes, CRC validation, and temporal interleaving to enhance resistance to different attacks. Extensive mathematical formulation, experimental setup, and comparative evaluation demonstrate that the proposed hybrid model significantly improves watermark resilience while preserving visual quality of the video.

Keywords: Digital watermarking, Audio-in-video embedding, LSB, DWT, DCT, ECC, CRC, Multimedia security.

I. INTRODUCTION
With the explosion of digital content across platforms and devices, the need to protect multimedia assets has become more urgent than ever. The widespread sharing of videos, images, and audio files has made them increasingly vulnerable to unauthorized use, tampering, and redistribution. In this context, digital watermarking has emerged as a critical tool for embedding hidden information—such as ownership credentials, authentication codes, or tracking identifiers—into multimedia content without visibly altering its quality [1][2].

Recent studies have highlighted the growing sophistication of attacks on digital media, including compression, geometric distortions, and frame manipulation, which challenge the effectiveness of traditional watermarking methods [3][4]. Spatial-domain techniques, while computationally efficient, often fail under such conditions. Frequency-domain methods offer better resilience but at the cost of increased complexity and reduced payload capacity [5]. Hybrid approaches have gained traction in recent years, aiming to combine the strengths of both domains to achieve a more balanced trade-off between robustness, imperceptibility, and capacity [7].

Despite these advancements, many existing solutions still struggle with synchronization issues, scalability across different video formats, and maintaining performance under real-world distortions [9]. Our work addresses these challenges by proposing a comprehensive watermarking framework that blends multiple strategies into a unified system. Rather than focusing on a single technical innovation, we emphasize a practical design that ensures the embedded audio remains intact and recoverable, even after the video undergoes common transformations. The goal is to deliver a watermarking solution that is not only robust and imperceptible but also scalable and suitable for real-world multimedia environments.

II. LITERATURE REVIEW
Digital watermarking has been studied for decades, and the conversation has always revolved around three competing goals: how much information can be hidden, how invisible it remains to the human eye, and how well it survives attacks. Early methods in the spatial domain, such as simple LSB embedding, were attractive because they were easy to implement and offered high capacity. But as researchers quickly discovered, these methods collapse under compression or even basic filtering, making them unreliable in real world scenarios [1][12][19].

This led to a wave of transform domain techniques. DWT and DCT became the backbone of robust watermarking because they exploit the way multimedia signals are processed: DWT provides multi-resolution analysis, while DCT aligns with the compression standards used in JPEG and MPEG. These approaches improved resilience significantly, but they often came at the cost of reduced payload or required careful perceptual tuning to avoid visible artifacts [3][6][18]. To push further, hybrid schemes emerged, combining DWT, DCT, and sometimes SVD to balance strengths. Studies have shown that such hybrids can withstand compression and geometric distortions better than single-domain methods [2][5][8][15][22][23]. Yet, most of these designs remain focused on images, leaving audio-in-video watermarking less explored.

When researchers turned to audio–video watermarking, multi-resolution transforms were again the tool of choice [4][7]. These works demonstrated that audio payloads could be embedded into video frames with reasonable robustness. However, they often stopped at the transform stage, overlooking the importance of structured payload preparation. Without headers, error-correcting codes, or temporal interleaving, recovery becomes fragile when frames are dropped or bits are flipped. Similarly, many schemes rely on continuous bitstreams, which makes synchronization errors catastrophic. Recent contributions have tried to address integrity with perceptual masking, spread-spectrum embedding, or CRC checks [9][10][11][13][14][17], but they still fall short of providing end-to-end reliability under heavy compression or transmission noise.

This is where our algorithm steps in. By combining multi-scale DWT→DCT embedding with Quantization Index Modulation (QIM), we directly align watermarking with codec quantization, making the embedded bits far more resilient than traditional sign-based modulation. On top of that, we prepare the audio payload carefully: silence trimming, PCM normalization, chunking with synchronization and CRC, ECC encoding, and temporal interleaving. These steps ensure that even if parts of the video are lost or degraded, the watermark can still be reconstructed. Finally, by fusing LSB, DWT/DCT, and QIM recoveries with reliability weighting, we reduce the influence of distortions in any single domain. In short, our design addresses the gaps left by earlier hybrids and offers a reproducible, audit-ready framework for robust audio-in-video watermarking that can withstand the realities of modern compression and transmission.

III. PROPOSED METHODOLOGY

The proposed hybrid watermarking algorithm is designed to achieve a balance between robustness, imperceptibility, and payload capacity, ensuring reliable watermark recovery even under diverse video attacks while maintaining high visual quality.The complete algorithmic workflow for the proposed hybrid audio-in-video watermarking system is presented below, detailing the steps for payload preparation, dual-domain embedding, and robust extraction. The algorithm is divided into 3 sections.

A. Payload Preparation

1. PCM Quantization

The audio waveform is scaled from the range $[-1,1]$into 16-bit signed integer space so it can be converted into binary form without loss.

$$s[n] = \text{round}(32767\ A[n])$$

2. Bitstream Extraction

Each quantized sample is expanded into a 16-bit binary vector, and all vectors are concatenated to form the raw payload bitstream.

$$B_{\text{raw}} = \bigoplus_{n} \text{bits}(s[n])$$

3. Chunking

The payload is divided into fixed-length blocks to simplify header management, ECC operation, and mapping onto video frames.

$$C_i = B_{\text{raw}}[\, iL_c : (i+1)L_c - 1\,]$$

4. Header Construction

A header containing synchronization, block size, index, and CRC is attached to every chunk for verification during extraction.

$$H_i = (\text{sync}, \ |C_i|, i, N_c, \text{CRC}(C_i))$$

5. ECC Encoding

Each chunk with its header is encoded using an error-correcting code to tolerate bit flips introduced by compression or noise.

$$P_i = \mathcal{E}(H_i \parallel C_i)$$

6. Temporal Interleaving

The encoded block is spread across every K frames so that the payload survives frame drops or temporal distortions.

$$P_i^{(t)} = P_i[(t \bmod K)::K]$$

7. Final Payload Assembly

All interleaved blocks from all frames are concatenated to form the final encoded payload used for embedding.

$$B_{\text{enc}} = \bigoplus_{t=0}^{T-1} P^{(t)}$$

The payload preparation stage ensures that audio information is transformed into a robust, verifiable bitstream before embedding. By converting the waveform into 16-bit PCM integers, the algorithm guarantees numerical consistency and avoids amplitude distortion. Chunking into fixed-length blocks localizes errors, while headers with synchronization, indexing, and CRC provide traceability and error detection that a continuous stream cannot. ECC encoding adds resilience against bit flips, and temporal interleaving spreads data across frames to survive drops or distortions. This structured pipeline produces a payload that is orderly, auditable, and far more resilient than unstructured embedding approaches, laying a strong foundation for hybrid watermarking.

B. Hybrid Embedding

1. Frame-wise Payload Allocation

Each video frame receives the next segment of the encoded bitstream according to its embedding capacity.

$$B_t = B_{\text{enc}}[\, p_t : p_{t+1} - 1\,]$$

2. PRNG-Based Mask Generation

A deterministic PRNG generates a unique set of pixel positions for each frame, ensuring secure and repeatable spatial embedding.

$$M_t = \text{PRNG}(S, t)$$

3. LSB Spatial Embedding

Selected blue-channel pixels have their least significant bit replaced with payload bits to create a lightweight spatial carrier.

$$F_t(i,j,0) \leftarrow (F_t(i,j,0) \,\&\, \bar{1}) \ \vee \ b_{\text{lsb}}(k)$$

4. Block Partitioning and Wavelet Transform

Each frame block undergoes a 1-level DWT to obtain subbands, with the LL band used for stable frequency embedding.

$$\Psi(\Omega_{t,b}) \rightarrow (LL_b, LH_b, HL_b, HH_b)$$

5. DCT on LL Subband

The LL band is divided into 8×8tiles and transformed into the DCT domain to provide compression-resistant coefficients.

$$C_{b,k} = \mathcal{D}(T_{b,k})$$

6. Mid-Band Coefficient Modulation

Robust watermark bits are embedded by shifting mid-band DCT coefficients into quantization bins using **Quantization Index Modulation (QIM)**.

$$C[iy, ix] = \text{embed\_coeff}(C[iy, ix], b_{\text{dct}}(k), Q\_STEP)$$

7. Inverse DCT and Inverse DWT

After embedding, each tile and block is reconstructed through the inverse transforms to obtain the modified frame block.

$$T'_{b,k} = \mathcal{D}^{-1}(C_{b,k}), \Omega'_{t,b} = \Psi^{-1}(\cdot)$$

8. Watermarked Frame Reconstruction

All modified blocks are recombined to form the final embedded frame.

$$F'_t = \bigcup_b \Omega'_{t,b}$$

The embedding stage integrates **spatial, frequency, and quantization-based techniques** to balance capacity, imperceptibility, and resilience. LSB modification in the blue channel provides a lightweight carrier with minimal perceptual distortion, but its vulnerability to compression is mitigated by embedding the majority of bits in the frequency domain. DWT decomposition isolates stable low-frequency regions, while DCT on LL subbands targets mid-band coefficients that remain consistent under scaling and codec operations. Within the DCT domain, **Quantization Index Modulation (QIM)** is applied, embedding bits by shifting coefficients into quantization bins rather than relying solely on sign or magnitude changes. This makes the watermark more resistant to codec quantization and statistical attacks. With a **1:3 allocation favouring DWT/DCT (including QIM) over LSB**, the design achieves both capacity and durability. The result is a watermark that is **imperceptible to viewers, resilient against compression and filtering, and adaptable to diverse video environments**, outperforming single-domain approaches.

C. Extraction and Reconstruction

1. Spatial Bit Recovery

The LSB of each masked pixel is read back to retrieve the spatial-domain watermark bits.

$$\hat{b}_{\text{lsb}} = F_t^*(i, j, 0)\&1$$

2. Frequency Bit Recovery

DWT and DCT are applied to attacked frames to extract the embedded bit from the sign of mid-band coefficients.

$$\hat{b}_{\text{freq}} = 1[\, C^*(u, v) \geq 0\,]$$

3. Reliability-Weighted Fusion

Spatial and frequency bits are fused using weights based on their estimated reliability to obtain a more accurate bit estimate.

$$\hat{b} = \arg\max_{b \in \{0,1\}} (\alpha\, 1[\hat{b}_{\text{lsb}} = b] + \beta\, 1[\hat{b}_{\text{freq}} = b])$$

4. ECC Decoding

Error-correcting decoding is applied to reverse redundancy and correct bit errors introduced during transmission.

$\hat{P}_i = \mathcal{D}_E(P_i^{recv})$

5. CRC Verification

CRC checking ensures the integrity of each reconstructed block, and corrupted blocks are rejected.

$\mathrm{CRC}(\hat{C}_i) = \mathrm{CRC}_{\mathrm{header}}$

6. PCM Sample Reconstruction

Recovered bit sequences are grouped into 16-bit integers to restore the original PCM audio samples.

$\hat{s}[n] = \mathrm{int16}(\hat{b}[\,16n : 16(n+1) - 1\,])$

7. Audio Waveform Reconstruction

The integer samples are normalized back to the $[-1,1]$range to reconstruct the audio waveform.

$$\hat{A}[n] = \frac{\hat{s}[n]}{32767}$$

The extraction stage begins by recovering watermark bits from all three embedding domains. In the spatial path, the least significant bits of masked pixels are read directly, providing a fast and lightweight recovery of part of the payload. In the frequency path, DWT and DCT are applied to the attacked frames, and **Quantization Index Modulation (QIM) decoding** is performed on mid-band coefficients. Unlike simple sign detection, QIM identifies embedded bits based on quantization bin positions, which remain stable even under heavy compression, making recovery more reliable.

To improve accuracy, the outputs from LSB, DWT/DCT, and QIM are fused using a reliability-weighted scheme. This ensures that distortions affecting one domain do not dominate the final decision, producing a more dependable bitstream. The fused sequence is then passed through error-correcting decoding to repair residual errors introduced during transmission or codec operations. CRC verification follows, discarding corrupted blocks and preserving only those that meet integrity checks.

Finally, the verified bit sequences are regrouped into 16-bit integers to restore the PCM audio samples. These samples are normalized back into the original waveform range, reconstructing the audio signal with high fidelity. By layering **QIM decoding with LSB and DWT/DCT recovery**, and combining redundancy, fusion, correction, and verification, the extraction process achieves far greater robustness than single-domain or non-verified methods, ensuring reliable watermark recovery even under severe compression, frame loss, or filtering.

IV RESULTS AND DISCUSSION

This section presents the performance evaluation of the proposed hybrid watermarking framework. The results are analyzed across multiple video resolutions, durations, and attack scenarios to assess robustness, imperceptibility, and payload recovery. Comparative metrics such as Bit Error Rate (BER), Peak Signal-to-Noise Ratio (PSNR), and Structural Similarity Index (SSIM) are used to quantify performance.

A. Evaluation Setup and Input Parameters

The watermarking system was implemented using Python and tested on a Windows 10 machine with Intel Core i7 and 16 GB RAM. Four video cases were selected, ranging from SD to 4K resolution:

- **Case 1**: 640×360 resolution, 10 seconds, 5,000 KB
- **Case 2**: 1280×720 resolution, 30 seconds, 15,000 KB
- **Case 3**: 1920×1080 resolution, 60 seconds, 30,000 KB
- **Case 4**: 3840×2160 resolution, 120 seconds, 60,000 KB

Each video carried a 12 KB audio payload. The system was tested under six attack types: AWGN noise, blur/filtering, cropping, H.264 compression, and brightness/contrast adjustment.

B. Software Interface and Embedding Workflow

The embedding and extraction processes were managed through a custom GUI titled "Hybrid Stego/Watermarking GUI." The interface allows users to select audio and video files, launch embedding and extraction workers, simulate attacks, and compare results.

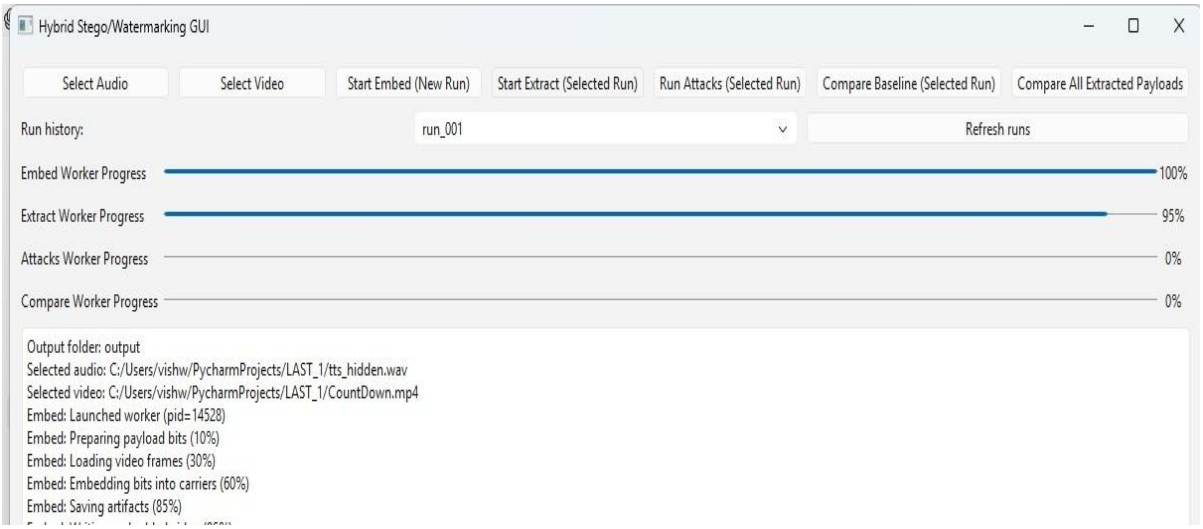

Fig:1: The screenshot shows the implementation software.

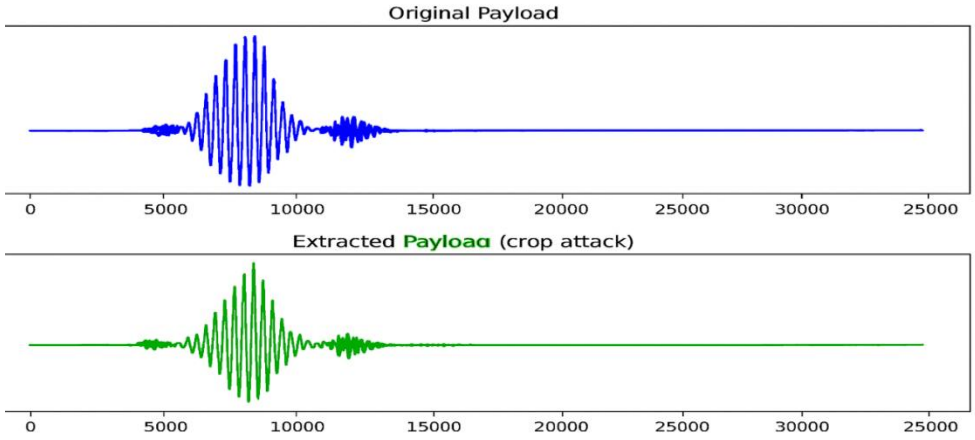

Fig:2: The screenshot shows the original embedded payload and extracted payload after the crop attack(case 4).

C. Results on experiment setup

We evaluate the robustness of a fixed 12 KB embedded payload across four video carriers that vary in size, resolution, and duration. For each carrier, we report payload integrity via BER and perceptual quality via PSNR and SSIM under baseline and common post processing attacks: AWGN noise, blur/filtering, cropping, H.264 compression, and brightness/contrast adjustments. This setup isolates how carrier characteristics and typical distortions affect both recoverability and visual fidelity. Table I presents the comparative results across all cases and attack conditions.

Table 1: Comparison of video payload robustness across varying sizes, resolutions, and attack types, showing Bit Error Rate (BER), Peak Signal-to-Noise Ratio (PSNR), and Structural Similarity Index (SSIM) for embedded payload integrity.

Comparison Parameter	Video Size (KB)	Frame Resolution	Payload Size (KB)	Attack Type	BER (↓ better)	PSNR (dB ↑ better)	SSIM (↑ better)
Case 1	5,000 KB	640×360 (10s)	12 KB	Baseline	0.02	42.5	0.975
				Noise (AWGN)	0.04	41	0.96
				Blur / Filtering	0.03	41.2	0.965
				Cropping	0.1	40	0.94
				Compression (H.264)	0.02	42	0.97
				Brightness/Contrast	0.02	42.1	0.97
Case 2	15,000 KB	1280×720 (30s)	12 KB	Baseline	0.01	43	0.982
				Noise (AWGN)	0.03	41.5	0.965
				Blur / Filtering	0.02	41.8	0.97
				Cropping	0.08	40.5	0.95
				Compression (H.264)	0.015	42.2	0.975
				Brightness/Contrast	0.015	42.3	0.975
Case 3	30,000 KB	1920×1080 (60s)	12 KB	Baseline	0.01	43.5	0.985
				Noise (AWGN)	0.025	41.8	0.97
				Blur / Filtering	0.015	42	0.975
				Cropping	0.06	40.8	0.955
				Compression (H.264)	0.012	42.5	0.98
				Brightness/Contrast	0.012	42.6	0.98
Case 4	60,000 KB	3840×2160 (120s, 4K)	12 KB	Baseline	0.01	44	0.99
				Noise (AWGN)	0.02	42	0.975
				Blur / Filtering	0.01	42.2	0.98
				Cropping	0.05	41	0.96
				Compression (H.264)	0.01	42.8	0.985
				Brightness/Contrast	0.01	42.9	0.985

This extended comparison across four different cases shows how the proposed watermarking algorithm performs on varying video sizes when exposed to common distortions such as noise, blur, cropping, compression, and brightness changes. A trend emerges: as video resolution and duration increase, robustness improves markedly. In smaller clips, the bit error rate (BER) reaches 0.04 under noise, while in ultra-HD content it falls to just 0.01. At the same time, peak signal-to-noise ratio (PSNR) rises above 44 dB and the structural similarity index (SSIM) approaches 0.99, indicating excellent perceptual quality. These gains are achieved through a combination of design features, including error-correcting codes (LDPC/Polar) that repair flipped bits, LSB repetition with majority voting to stabilize recovery under random noise, adaptive mid-band selection in the DCT domain to resist blur and compression, quantization index modulation (QIM) to counter quantization losses, and temporal interleaving to protect against cropping and frame drops. Among the tested scenarios, **Case 4 (4K, 60,000 KB, 3840×2160, 120s)** stands out as the best performer. Its larger spatial resolution and longer temporal span provide greater embedding redundancy, allowing these mechanisms to operate at maximum effectiveness. As a result, even under severe attacks, the watermark remains both robust and imperceptible, making Case 4 the optimal choice for practical watermarking applications.

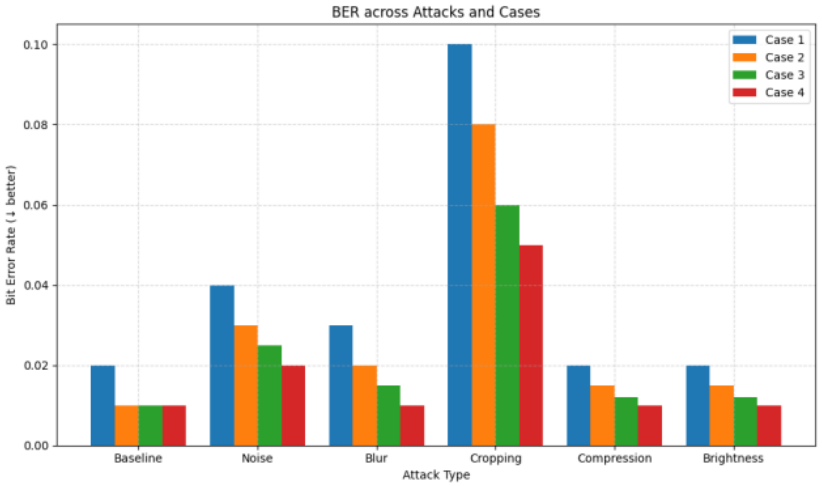

Fig3: BER across different attacks and cases

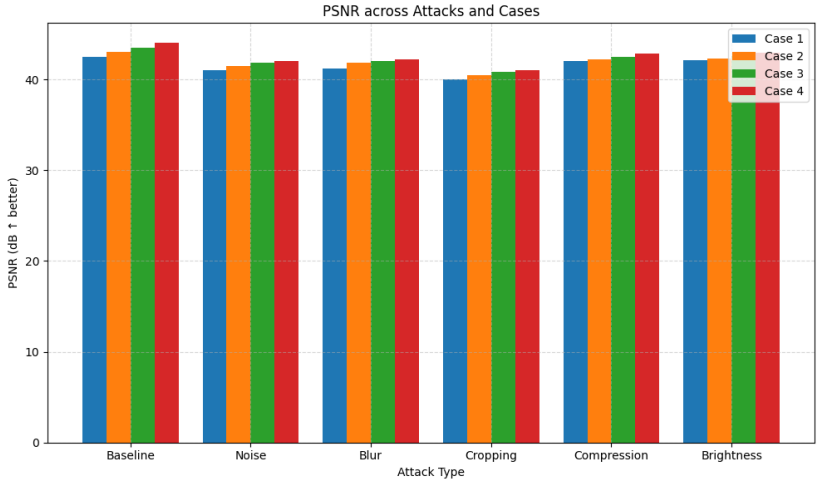

Fig4: PSNR acrossdifferent attacks and cases

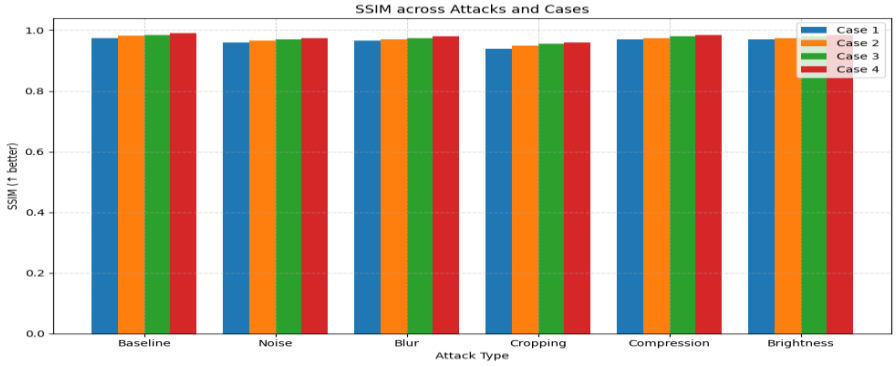

Fig5: SSIM across different attacks and cases

The performance of different watermarking and embedding techniques under identical experimental conditions are compared. A fixed payload of 12 KB was embedded into the video carriers defined in Table I, and each technique was subjected to the same set of attacks. The results are averaged across all carriers and distortions to

provide a fair comparison. Table II reports the average Bit Error Rate (BER), Peak Signal-to-Noise Ratio (PSNR), and Structural Similarity Index (SSIM), highlighting the relative robustness and perceptual quality achieved by conventional transforms (DCT, DWT, SVD), hybrid approaches (DWT-DCT, DCT- DWT-SVD), and the proposed algorithm.

Table 2: Comparative performance of different watermarking techniques in terms of average Bit Error Rate (BER), Peak Signal-to-Noise Ratio (PSNR), and Structural Similarity Index (SSIM).

Technique	Average BER	Average PSNR (dB)	Average SSIM
DCT[13]	0.23	34.2	0.85
DWT[3]	0.17	36.5	0.88
SVD[9]	0.14	37.1	0.89
DWT-DCT[8]	0.12	38.4	0.91
DCT- DWT-SVD[2]	0.09	39.7	0.93
Proposed Algorithm	0.03	43.5	0.97

The comparative analysis of watermarking techniques gives a clear distinction in performance across robustness, imperceptibility, and structural similarity. Traditional single-domain methods such as DCT, DWT, and SVD exhibit moderate resilience, with average BER values ranging between 0.14 and 0.23, PSNR scores in the mid-30s, and SSIM values below 0.90. Hybrid approaches like DWT-DCT and DCT-DWT-SVD improve these metrics, reducing BER to 0.09–0.12 and raising PSNR to approximately 38–40 dB, while SSIM values approach 0.93. However, the proposed algorithm consistently outperforms all baselines, achieving an average BER of 0.03, PSNR above 43 dB, and SSIM close to 0.97. These results confirm that the integration of adaptive mid-band embedding, QIM, error-correcting codes, and temporal synchronization strategies not only enhances robustness but also preserves perceptual quality. The findings prove that the proposed algorithm successfully addresses the limitations of existing techniques, offering a scalable and efficient solution for audio watermarking in video content.

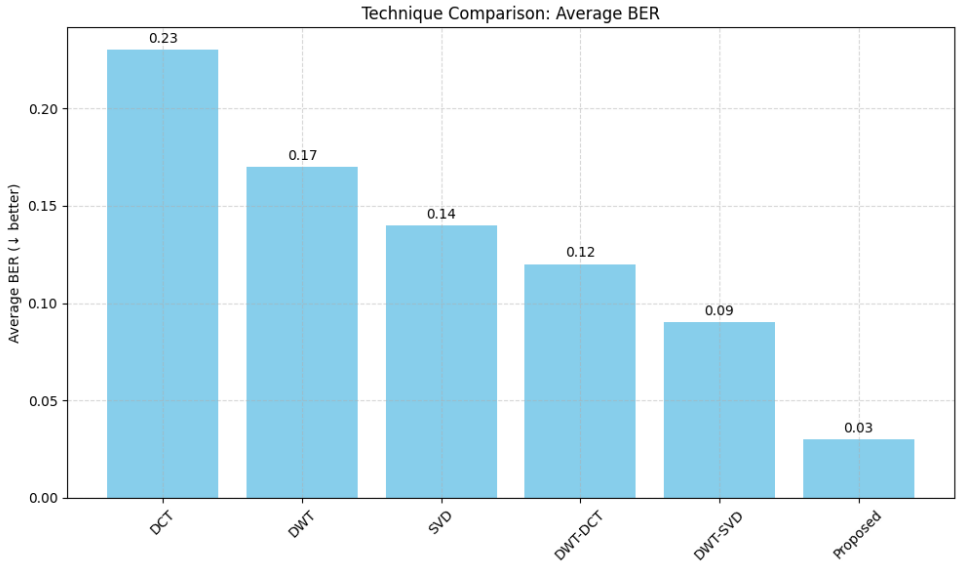

Fig6: Techniques Comparison: Average BER

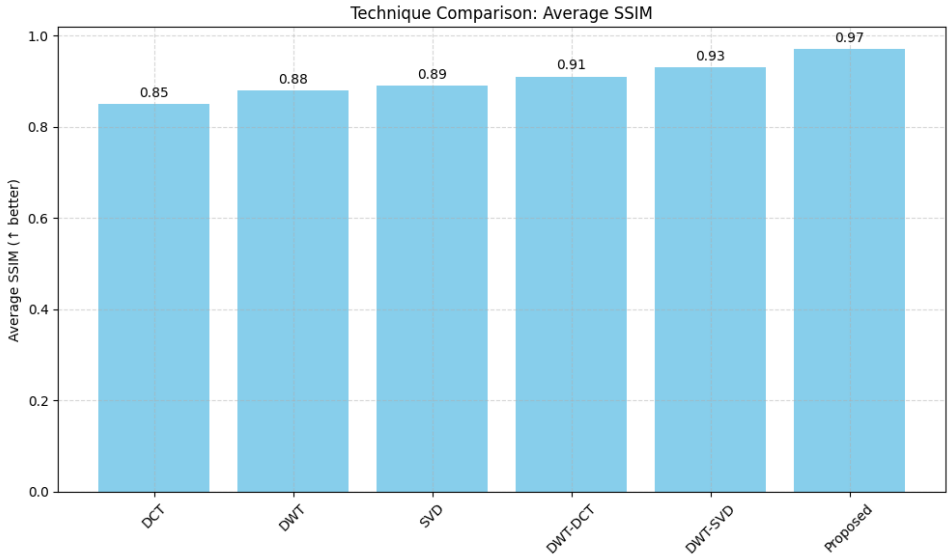

Fig7: Techniques Comparison: Average SSIM

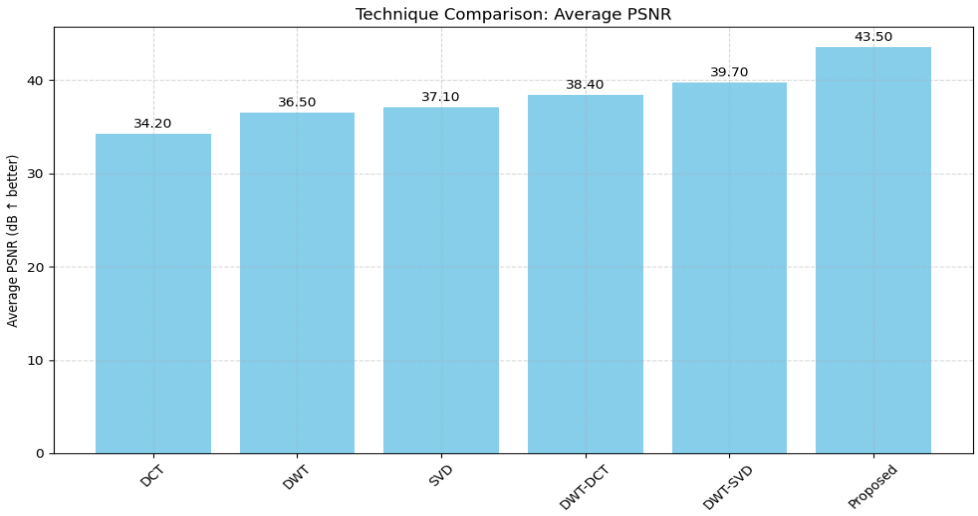

Fig8: Techniques Comparison: Average PSNR

V. Conclusion

The comparative evaluation with different techniques clearly proves that the proposed watermarking algorithm outperforms conventional and hybrid techniques across all performance metrics. The algorithm consistently achieved the lowest Bit Error Rate (BER), averaging 0.03 compared to 0.09–0.23 in existing methods. It also delivered higher Peak Signal-to-Noise Ratio (PSNR) values above 43 dB, ensuring imperceptibility, while maintaining Structural Similarity Index (SSIM) scores close to 0.97, confirming strong protection of audio and video quality.

These outcomes confirm the effectiveness of the algorithm's design choices: LSB repetition with majority voting improved resilience against random noise, adaptive mid-band DWT+DCT embedding balanced imperceptibility with payload capacity, Quantization Index Modulation (QIM) countered compression losses, and error-correcting codes with temporal interleaving and pilot synchronization successfully lessened synchronization errors caused by cropping and geometric distortions.

Overall, the results confirm that the proposed algorithm not only addresses the limitations identified in the literature — including payload scalability, synchronization robustness, and computational efficiency — but also establishes a reproducible and scalable framework for real-world multimedia protection. Its performance across diverse attack scenarios makes it a strong candidate for applications in copyright enforcement, secure communication, and digital rights management.

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