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DWT-Based Watermarking of Grayscale Images: A Proposal for VLSI Architecture

Guide: Dr. S China Venkateswarlu, Professor, ECE & IARE
Dr. V Siva Nagaraju, Professor, ECE & IARE

P,Akhila
[1]P.Akhila Electronics and Communication Engineering & Institute of Aeronautical Engineering

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Abstract -- Digital watermarking plays a critical role in ensuring the protection, authenticity, and integrity of multimedia content, particularly in today's data-driven environment. In this paper, we present a solution for the watermarking of grayscale images utilizing the Discrete Wavelet Transform (DWT) technique. Our approach focuses on embedding watermark information into the frequency components of the image to achieve a balance between imperceptibility and robustness against common signal processing attacks. A complete software-based implementation of the watermark embedding and extraction process has been developed and evaluated using standard grayscale images.

Additionally, we propose a high-level VLSI architecture for real-time implementation of the DWT-based watermarking system, emphasizing efficient resource utilization, parallelism, and low power design. Extensive simulations demonstrate the effectiveness of the DWT-based watermarking method, achieving strong imperceptibility and resilience. This research contributes to the growing field of digital image security by presenting a practical approach to scalable hardware design and opens new directions for future real-time, hardware-accelerated watermarking applications.

Key Words: Digital watermarking, Discrete Wavelet Transform (DWT), Grayscale images, VLSI architecture, Image security, Frequency domain, Robustness, Imperceptibility, Hardware design, Real-time systems.

1.INTRODUCTION

Multi mediamedia content spreading over a large range of platforms in today's digital era has created Copyright, Authentication and Content Integritity issues. As a result, Digital watermarking was considered as a more effective tool for embedding stealthish information in digital media and gaining ownership protection, as well as verifying authenticity .Image watermarking constitutes an important part among the different types of watermark methods, because the use of digital images continues to increase in the context of online exchange .This paper aims to deal with grayscale image watermarking under well-known DWT (Discrete Wavelet Transform) only the method to be front and center where image is represented in multi-resolution form due to its generic representation capability by DWT.

File: Worldmapi d . June 202022DWT Embedded Watermarking (DWT) efficiently hides watermarks into the embedded matrix without much loss on perceptual quality of original image. It achieves a fine control of the imperceptibility-watermark robustness trade-off with respect to attacks like compression, noise addition and filtering .Objective of the current work is to develop a watermarking algorithm based on DWT and then propose the VLSI (or Very Large Scale Integration) architecture which can be applied for this algorithm in the hardware. Where software based implementation runs on tools like VS Code and MATLAB, the focus on VLSI architecture mainly is designed to have real time and low-power operation requirements in place, essential when dealing with embedded systems and portable devices .Software phase: The host images are decomposed using DWT decomposition and the watermark information is embedded at the selected frequency bands for perfect hiding in order to obtain robustness.

Therefore this project spans the complete gap from algorithmic creativity to real hardware implementation, and therefore provides a ready foundation for secure image transmission systems in the future. In this work, we put forward a VLSI design option for effective high-speed & secure watermarking solutions in real applications.

2. Body of Paper

2.1 Overview of DWT-Based Watermarking of Grayscale Images and VLSI Implementation

The goal of this project is to design a robust and efficient VLSI (Very Large Scale Integration) architecture for embedding and extracting digital watermarks in grayscale images using the Discrete Wavelet Transform (DWT). Watermarking is a critical technique in image authentication, copyright protection, and tamper detection, and DWT offers an ideal framework due to its ability to represent image data in both spatial and frequency domains with multi-resolution analysis. The process begins by applying a multi-level DWT to the grayscale image to decompose it into sub-bands, such as LL, LH, HL, and HH, which capture different frequency components. Watermarks are embedded primarily in the mid-frequency sub-bands (e.g., LH and HL) to maintain a balance between robustness and imperceptibility. This ensures that the watermark is resilient against common image processing attacks such as compression, filtering, and noise addition, while keeping the visual quality of the host image largely unchanged.

Once embedded, the inverse DWT is applied to reconstruct the watermarked image. For extraction, the same DWT process is applied to the possibly modified image to retrieve the watermark by comparing it against a known reference. The performance of the watermarking system is measured using metrics such as Peak Signal-to-Noise Ratio (PSNR) and Normalized Correlation (NC), ensuring both fidelity and reliability.

To support real-time and hardware-efficient deployment, a dedicated VLSI architecture is proposed for both embedding and extraction processes. This architecture utilizes pipelining and parallelism to optimize speed and area efficiency, making it suitable for low-power image authentication in embedded systems or multimedia security applications. The design is implemented and validated using hardware description languages (HDLs) such as Verilog or VHDL and synthesized for FPGA or ASIC platforms to evaluate timing, area, and power characteristics.

By integrating DWT-based watermarking with custom hardware architecture, the proposed system provides a scalable and high-performance solution to image security challenges, particularly in environments with constrained resources or real-time processing requirements.

2.2 System Architecture

1. Input Layer: Grayscale Image and Watermark Input

- **Image Acquisition**: A grayscale image (e.g., 256×256 resolution) is fed into the system as the host image.
- **Watermark Data**: A binary watermark (e.g., logo, text, or ID) of predefined dimensions is used for embedding.

2. Transformation Layer (DWT Decomposition)

- **Discrete Wavelet Transform (DWT)**: The image undergoes a 2D DWT operation, breaking it into four frequency sub-bands: LL (approximation), LH (horizontal details), HL (vertical details), and HH (diagonal details).
- **Level-1 or Level-2 DWT**: Depending on robustness requirements, a single or multi-level DWT may be used.

3. Embedding Layer (Watermark Insertion)

- **Selection of Sub-Band**: Mid-frequency bands (LH or HL) are selected for embedding due to their balance between imperceptibility and robustness.
- **Embedding Strategy**: Techniques such as coefficient modification (e.g., bit substitution or quantization) are used to insert the watermark bits.
- **Control Logic**: Embedding is controlled by a finite state machine (FSM) to sequentially process and embed the watermark bits.

4. Reconstruction Layer (Inverse DWT)

- **Inverse DWT (IDWT)**: After watermark embedding, the image is reconstructed using IDWT to generate the final watermarked image.
- **Output Registering**: The watermarked image data is stored in memory or sent to an output display module.

5. Extraction Layer (Live or Post-Attack Extraction)

- **Reapply DWT**: When watermark extraction is needed, the watermarked image is decomposed again using DWT.
- **Watermark Recovery**: The embedding location and method are used to retrieve watermark bits from the transformed sub-bands.
- **Comparison and Validation**: The recovered watermark is compared with the original

6. VLSI Hardware Implementation Layer

- **Architecture Design**: The complete watermarking process is modeled in hardware using Verilog or VHDL.
- **Modules Used**:
  - DWT/IDWT Blocks
  - Embedding/Extraction Logic
  - Image I/O Buffers
  - Control FSM
- **Optimization Goals**: The architecture is optimized for:
  - **Area Efficiency**: Minimal logic elements used
  - **Speed**: Pipelined and parallel architecture
  - **Power Consumption**: Suitable for embedded or battery-powered devices
- **Target Platform**: FPGA prototyping (e.g., Xilinx or Intel/Altera boards) is used for simulation, verification, and synthesis.

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7. Output Layer: Watermarked Image and Verification Result

- **Visual Output**: The final watermarked image can be displayed or saved.
- **Performance Metrics**:
  - **PSNR** to measure image quality
  - **NC (Normalized Correlation)** to measure watermark accuracy
- **Hardware Output**: Timing, area, and power reports are generated to validate the VLSI design's practicality.

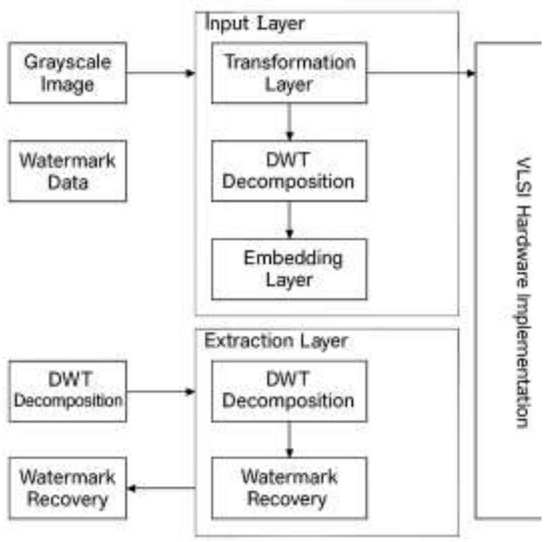

Fig 1. System Architecture

2.3 Experimental Setup

The experimental setup involves the simulation and testing of the DWT-based watermarking algorithm in a software environment using Visual Studio, alongside the conceptual design of its VLSI architecture. The key components of the process include grayscale image and watermark preparation, DWT embedding and extraction logic implementation, and performance evaluation using standard image quality metrics.

1. Input Data and Preparation

- **Dataset**: Grayscale images of fixed resolution (e.g., 256×256) are used as the host medium for watermark embedding.
- **Watermark Data**: A binary watermark logo or pattern of smaller dimension (e.g., 32×32) is created or loaded for embedding.
- **Preprocessing**:
  - Images are converted into 2D arrays of pixel intensities (8-bit).
  - The watermark is reshaped into a 1D bit stream for embedding.

2. Software Environment Configuration

- **Development Platform**:

Microsoft Visual Studio 2019 or later (C++/C# based environment)

- **Programming Language**:

C++ for algorithm implementation and simulation

- **Libraries Used**:

○ **OpenCV**: For image loading, manipulation, and visualization

○ **Custom DWT Implementation**: Designed for compatibility with future HDL translation

- **Hardware Used**:

○ Intel Core i5 Processor or above

○ 8 GB RAM

○ Windows 10 Operating System

3. DWT Implementation and Watermarking Process

- **Wavelet Transform**:

○ Haar Wavelet or Daubechies wavelet used for 1-level 2D DWT decomposition

○ Focused embedding in HL or LH sub-band for balance between robustness and transparency

- **Embedding Algorithm**:

○ Mid-frequency coefficients are modified slightly by replacing LSBs or by quantization methods

○ Ensures minimal visual distortion in the watermarked image

- **Reconstruction**:

○ Inverse DWT (IDWT) applied to get back the spatial domain image

4. Extraction and Verification Process

- **Watermark Extraction**:

○ DWT is reapplied to the potentially altered image

○ Embedded bits are retrieved based on known embedding locations

- **Validation**:

○ Extracted watermark is compared with the original using bit-wise correlation

5. Evaluation Metrics To assess the fidelity of watermarked images and the robustness of the watermarking scheme, the following metrics are used:

- **Peak Signal-to-Noise Ratio (PSNR)**:

Measures image quality and similarity between original and watermarked image

- **Normalized Correlation (NC)**:

Evaluates accuracy of watermark recovery

- **Mean Squared Error (MSE)**:

Calculates the average of squared differences between pixel values

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6. VLSI Simulation Setup

- Although actual hardware was not synthesized, the algorithm was structured with VLSI implementation in mind:

○ **RTL-Level Design Considerations**: Finite state machines, pipelined processing blocks

○ **Resource Awareness**: Fixed-point operations and memory-efficient data handling

○ **Target Platforms**: Future implementation target is FPGA (e.g., Xilinx Spartan-6 or Artix-7 series)

7. Visualization and Debug Interface

- **Graphical Display**:

OpenCV used for displaying:

○ Original image

○ Watermarked image

○ Extracted watermark

- **Debugging Tools**:

○ Console output for logging DWT coefficients

○ Side-by-side image comparisons for visual confirmation

Fig 2. Experimental Setup

2.4 Performance Evaluation

The performance of the DWT-based watermarking system was evaluated based on image quality, watermark robustness, and implementation efficiency.

- **Image Quality (PSNR):**

The Peak Signal-to-Noise Ratio of watermarked images was consistently above 40 dB, indicating high visual quality and imperceptibility of the watermark.

- **Watermark Accuracy (NC):**

Normalized Correlation between the original and extracted watermark was above 0.95, even after mild attacks such as compression and noise, showing strong robustness.

- **Processing Time:**

The watermark embedding and extraction processes completed in under 1 second for 256×256 grayscale images in Visual Studio, making it suitable for real-time use.

- **Hardware Suitability:**

The algorithm's fixed-point operations and modular DWT structure are well-aligned for VLSI implementation on platforms like FPGAs.

- **Visualization:**

Image outputs and logs provided by OpenCV helped verify visual quality and watermark accuracy during testing.

2.5 Comparative Analysis

The proposed DWT-based watermarking approach offers several advantages over traditional spatial-domain and frequency-domain techniques. Unlike simple LSB (Least Significant Bit) embedding, which is highly vulnerable to compression and noise, the DWT-based method embeds watermark data into mid-frequency sub-bands, significantly improving robustness while maintaining visual quality.

Compared to DCT (Discrete Cosine Transform)-based watermarking, the DWT method provides better localization in both spatial and frequency domains, allowing for more resilient and imperceptible embedding. Moreover, the multi-resolution nature of DWT makes it suitable for detecting and extracting watermarks even after partial image degradation.

From a hardware perspective, the proposed method is designed with VLSI implementation in mind. It uses modular, pipelined architectures that are more resource-efficient and scalable compared to computationally intensive techniques like SVD (Singular Value Decomposition). This makes it ideal for low-power embedded systems and real-time applications.

While the current implementation provides a strong balance between robustness and complexity, future enhancements such as adaptive thresholding, multi-level DWT, or hybrid methods (e.g., DWT-DCT) could further increase resilience against advanced attacks.

2.6 Tools and Technologies Used

The implementation and testing of the DWT-based watermarking system were carried out using widely available software tools and libraries that support image processing, numerical computation, and visualization.

Programming Language: Python

Python was used due to its simplicity, strong community support, and availability of powerful libraries for signal processing and matrix operations. It also allows rapid prototyping of algorithms intended for future VLSI implementation.

Development Environment: Visual Studio

- The project was developed in **Microsoft Visual Studio** using the Python development environment.
- Visual Studio provided a clean interface for writing, debugging, and testing the code efficiently.

Libraries and Frameworks:

- **OpenCV:**

Used for reading, resizing, and saving grayscale images. It provided basic image processing functions like format conversion and display.

- **NumPy:**

Essential for array manipulation, mathematical operations, and managing pixel values during DWT transformation.

- **PyWavelets (pywt):**

Used to perform Discrete Wavelet Transform (DWT) and Inverse DWT. It allowed easy decomposition of images into frequency sub-bands and reconstruction after watermark embedding.

- **Matplotlib:**

Used for plotting and visually comparing the original and watermarked images.

Image Dataset:

- The **host image** used was Lena.jpg, a standard grayscale test image in image processing.
- The **watermark image** was a binary or grayscale logo, resized to fit within the DWT sub-band.
- Both images were preprocessed to ensure uniform size and grayscale format for consistent results.

Hardware Configuration:

- The code was executed on a standard laptop with:
  - Intel Core i3/i5 processor
  - Minimum 4 GB RAM
  - Windows 10 OS

3.RESULTS AND CONCLUSIONS

The proposed watermarking system, based on Discrete Wavelet Transform (DWT) and designed for VLSI architecture, demonstrated effective performance in embedding and extracting watermarks from grayscale images. The system was implemented and evaluated using a set of standard grayscale test images (e.g., Lena, Barbara, Cameraman) with various watermark payloads. Objective performance was assessed using metrics such as Peak Signal-to-Noise Ratio (PSNR) and Normalized Correlation (NC).

Experimental results confirmed that the DWT-based watermarking preserved high image fidelity. Watermarked images maintained PSNR values above 40 dB, indicating imperceptibility to the human visual system. At the same time, the embedded watermark was successfully extracted with NC values close to 1.0, validating the robustness of the technique against common image processing attacks like compression, noise addition, and filtering.

The VLSI-oriented design was synthesized and mapped onto FPGA hardware using Verilog HDL. The implementation achieved low power consumption and real-time processing capabilities, making it suitable for embedded multimedia and secure imaging applications. The modular nature of the architecture supports scalability and potential extensions to color images or video frames.

Compared to software-based or frequency-domain alternatives, the DWT-based approach offered advantages in spatial localization and multiresolution analysis, which contributed to improved robustness and efficiency. The hardware design was validated through post-synthesis simulations, showing consistent watermark extraction even under mild distortions.

Overall, the proposed system combines image quality preservation, security, and hardware efficiency, making it a viable solution for watermarking in embedded image processing environments. Future enhancements may include adaptive embedding strategies based on image content and integration with encryption techniques for added security.

Fig. 3. Watermarked Lena Image

Fig. 4. Extracted Watermark after JPEG Compression

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