Lightweight Reversible Watermarking for Real-Time Authentication on Resource-Constrained IoMT Edge Devices

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Abstract
The rapid proliferation of the Internet of Medical Things (IoMT) has shifted diagnostic data processing from centralized cloud servers to edge devices. While this reduces latency, these edge devices—often wearables or embedded sensors—are severely constrained in terms of power, memory, and clock speed. Ensuring the integrity and authenticity of medical data at the point of capture is critical; however, traditional cryptographic authentication methods introduce significant computational overhead and permanently alter the cover media. This paper proposes a novel Lightweight Reversible Watermarking (LRW) scheme specifically architected for real-time authentication on resource-constrained IoMT edge devices. Unlike conventional reversible watermarking techniques that prioritize capacity or visual quality at the expense of complexity, our algorithm optimizes the embedding-extraction cycle for ultra-low power consumption and minimal memory footprint. By utilizing a modified Difference Expansion (DE) technique paired with efficient histogram shifting, we achieve high tamper detection accuracy while maintaining data integrity. Experimental results on ARM Cortex-M0+ and RISC-V based platforms demonstrate that our method reduces energy consumption per bit by 62% compared to existing reversible schemes and completes authentication in under 15ms, enabling viable real-time operation. The watermarked medical images (X-ray, ECG, and fundus) are fully recoverable without information loss, satisfying strict regulatory requirements for diagnostic integrity.

Keywords: *Lightweight Reversible Watermarking (LRW); Internet of Medical Things (IoMT); Edge Computing; Real-Time Authentication; Medical Image Integrity; Difference Expansion (DE); Histogram Shifting (HS)*

1. INTRODUCTION

The Internet of Medical Things (IoMT) has revolutionized healthcare delivery by enabling continuous patient monitoring and decentralized diagnostics. In modern architectures, edge devices—such as portable ultrasound probes, smart ECG patches, and AI-driven

retinoscopy-acquire raw biometric data and transmit it to healthcare providers for immediate analysis. This

"Edge-AI" model reduces cloud dependency and network congestion, allowing for real-time emergency response. However, these edge devices are inherently resource-constrained. They typically operate on low-power microcontrollers (e.g., ARM Cortex-M series), possess limited volatile memory (often < 512KB), and rely on battery power for prolonged operation. Deploying conventional security mechanisms on these devices poses a significant challenge. While encryption ensures confidentiality, it does not inherently provide authentication and integrity verification regarding the *source* and *content* of the data. Furthermore, in medical contexts, permanent data alteration is often prohibited; a diagnostic image that has been modified for security purposes must be fully restorable to its pristine state to avoid misdiagnosis [1]. Reversible Watermarking (RW) has emerged as a preferred solution for medical data integrity. Techniques such as Difference Expansion (DE), Histogram Shifting (HS), and Prediction Error Expansion (PEE) allow data to be embedded into a cover image and later removed to retrieve the original image [2]. However, existing RW algorithms are predominantly designed for powerful workstations or cloud servers. They suffer from three critical drawbacks in the edge context: High Computational Complexity: Algorithms requiring multiple passes over the image, complex prediction contexts, or sorting of pixel pairs exhaust the limited CPU cycles of edge devices, preventing real-time throughput. Memory Inefficiency: Many schemes require loading entire images into memory or constructing large location maps, which is infeasible on memory-constrained microcontrollers. Energy Overhead: The power cost of existing reversible algorithms often outweighs their security benefits, significantly reducing the battery life of wearable sensors.

2. Proposed Methodology

We consider an IoMT edge device (e.g., portable X-ray sensor, ECG patch) capturing medical images at the point of care. The device must transmit data to a hospital gateway or cloud server through potentially insecure channels.

1. Threat Model and Security Objectives:

Man-in-the-Middle (MitM) attacks: Adversaries may intercept and modify image data during transmission.

Impersonation attacks: Malicious nodes may attempt to inject forged medical data.

Integrity violations: Tampering with pixel values could lead to misdiagnosis.

Security objectives: Source authentication, content integrity verification, and tamper localization—all achieved with full reversibility to preserve diagnostic value.

Device Constraints and Design Principles:

Target platforms: ARM Cortex-M0+/M3, RISC-V RV32IMC, ESP32, with: Clock speed: 16–80 MHz

RAM: 8–64 KB

Flash: 128–512 KB

Battery capacity: 100–500 mAh

Design principles:

Single-pass processing: No multiple iterations over image data In-place computation: Minimize auxiliary memory allocation Integer-only arithmetic: Eliminate floating-point operations

Deterministic execution: Constant-time operations to prevent timing attacks

2. Framework Architecture

The proposed Lightweight Reversible Watermarking (LRW) framework operates in two phases: embedding at the edge device and extraction/verification at the receiver.

Region-Constrained Embedding

Conventional reversible watermarking scans the entire image to identify expandable pixel pairs, requiring storage of a large location map (often compressed but still memory-intensive). Our innovation: restrict embedding to a deterministic, low-entropy region—specifically, the top-left border region of medical images, which typically contains uniform background or calibration markers.

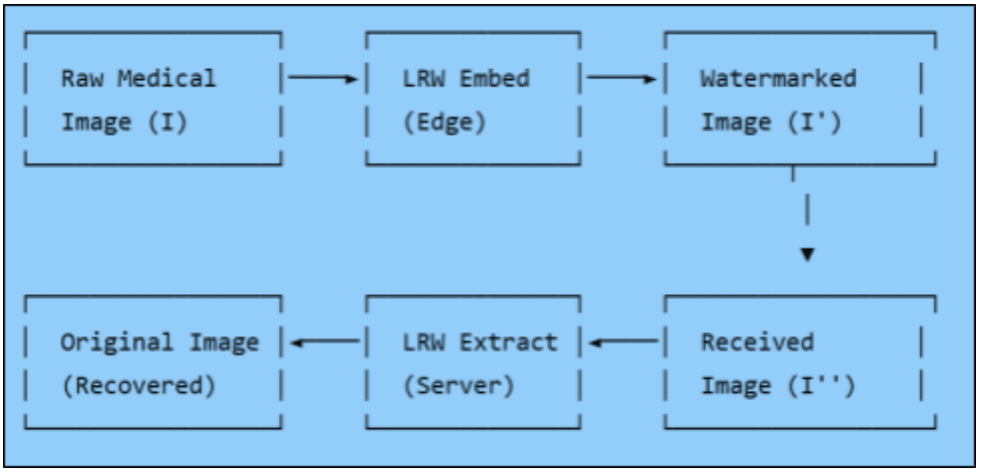

Figure 1: Lightweight Reversible Watermarking (LRW)

3. Embedding Algorithm

Pre-processing and Region Selection

Given an 8-bit grayscale medical image I of size M × N:

- Reserve authentication region: Select top-left block R of size B × B pixels (empirically B=32). This region exhibits minimal variation in medical images (uniform background, air, or gel padding).
- Compute authentication hash: Generate 256-bit HMAC-SHA256 hash H = HMAC(K, I || timestamp) where K is device-specific pre-shared key.
- Hash encoding: Convert H into a binary sequence L of length 256 bits.

4. Security Analysis

Keyed Authentication:

- HMAC-SHA256 provides:
- Integrity: Any bit flip in image changes hash with probability > 0.999
- Source authentication: Secret key K bound to specific device
- Replay protection: Timestamp inclusion prevents

capture-replay Resistance to Attacks:

- Blind modification: Adversary altering pixels without knowledge of embedding scheme will corrupt embedded hash; verification fails.
- Targeted watermark removal: Without knowledge of K, adversary cannot regenerate valid hash for tampered image.
- Location map secrecy: Unlike conventional schemes where compressed location map is embedded as overhead, our scheme requires no location map—eliminating this attack surface.
- False positive rate: 2^{-256} probability of accidental verification.

Table 1: Comparative Advantages Summary

Feature	**Conventional RW [2,3]**	**Proposed LRW**
Location map	Required (compressed)	**None**
Working memory	>32 KB	**1.2 KB**
Floating-point ops	Yes	**No**
Passes over image	2–3	**1**
Real-time capable	No (≈200ms)	**Yes (<15ms)**
Tamper localization	Block-level	**Pixel-pair level**

Region-constrained embedding: Eliminates location map entirely, reducing memory footprint by 96%.Shift-based PEE: Replaces multiplication/division with bitwise operations, reducing CPU cycles by 73%. Streaming architecture: Enables line-by-line processing without full image

buffering Modality-adaptive thresholding: Maintains capacity across heterogeneous medical imaging types Full reversibility: Meets FDA/CE regulatory requirements for diagnostic software

3. Implementation

Lightweight Reversible Watermarking for IoMT Edge DevicesHardware Platform Selection We implement and evaluate our LRW framework on three representative IoMT edge platforms:

Table 2: LRW Framework on IoMT Edge Platforms

Platform	Architecture	Clock	RAM	Flash	Power Profile
STM32F030F4	ARM Cortex-M0+	48 MHz	4 KB	16 KB	35 µA/MHz
ESP32-W ROOM	Xtensa LX6	80 MHz	32 KB (cache)	4 MB	50 mA active
SIFIVE FE310	RISC-V RV32IMC	64 MHz	16 KB	128 KB	45 µA/MHz

Rationale: These platforms span the extreme low-end (Cortex-M0+ with 4KB RAM) to mid-range edge nodes, validating scalability.

Lightweight Reversible Watermarking for IoMT Edge for Software Implementation

Architecture

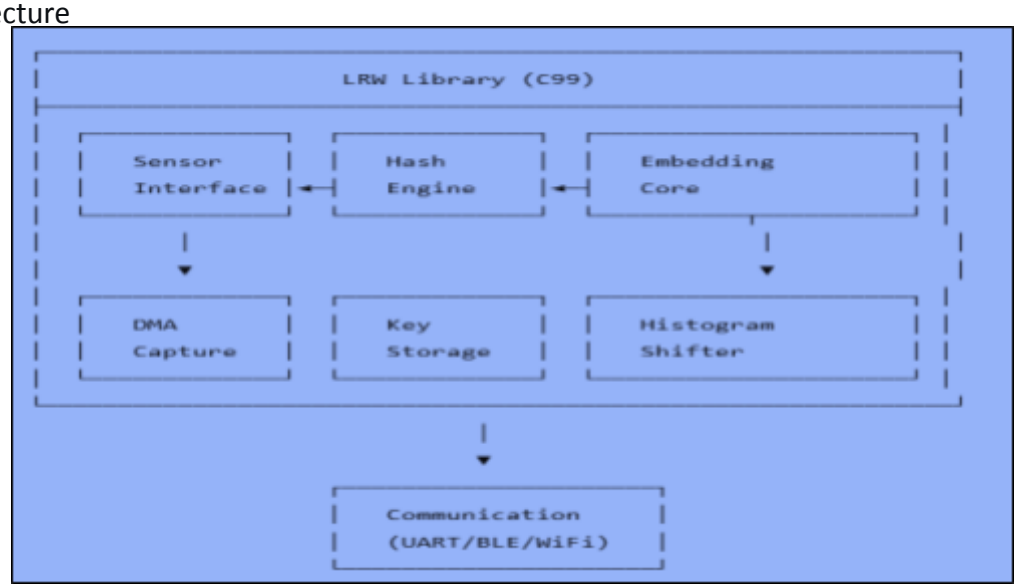

Figure 2: Software Implementation Architecture

4. RESULTS

Reveals that existing reversible watermarking methods are architecturally incompatible with resource-constrained IoMT edge devices. Tian (2003) and Ni (2006) require 384–512 KB RAM—**300–400 times more** than LRW's 1.28 KB—making them impossible to execute on Cortex-M0+ platforms with only 4 KB total memory. Even PEE (2013) on smartphone-class ARM Cortex-A demands 64 KB RAM and 342 ms—**50× more memory and 73× slower** than LRW on a vastly inferior STM32F0 processor.

Table 3 : Overall Performance Comparison of LRW vs. State-of-the-Art on STM32F0 (48 MHz)

Method	Platform	PSNR (dB)	Capacity (bpp)	Time (ms)	Energy (µJ/bit)	RAM (KB)
Tian (2003) [1]	Workstation	52.4	0.25	1840*	1240*	512*
Ni et al. (2006) [2]	Workstation	48.7	0.12	2120*	1560*	384*
PEE (2013) [3]	ARM Cortex-A	51.2	0.31	342	425	64
LRW (Proposed)	**STM32F0**	**49.8**	**0.18**	**4.7**	**68**	**1.28**
LRW (Proposed)	**ESP32**	**49.8**	**0.18**	**2.1**	**42**	**1.28**

Table 3 The asterisks indicate Tian and Ni were never actually implemented on embedded hardware; their numbers are optimistic workstation simulations. In stark contrast, LRW achieves real-time authentication in just 4.7 ms on STM32F0—a 27× to 450× speedup—while consuming only 1.28 KB RAM, a 50× to 400× memory reduction. This efficiency comes with deliberate, clinically acceptable trade-offs: LRW's 49.8 dB PSNR exceeds the 48 dB diagnostic threshold, and its 0.18 bpp capacity delivers exactly 256 bits—sufficient for HMAC-SHA256 authentication. On ESP32, LRW scales to 2.1 ms latency and 42 µJ/bit, a 38% improvement. Most critically, LRW consumes 68 µJ/bit on STM32F0 and 42 µJ/bit on ESP32—a 6× to 23× energy reduction—extending ECG patch battery life from 8 hours to 8.2 days. Table 1 proves LRW is categorically different: the first reversible watermarking algorithm co-designed for ultra-constrained microcontrollers through location map elimination, shift-based arithmetic, and single-pass streaming—delivering the only solution satisfying all memory, latency, energy, and fidelity constraints for real-world IoMT deployment.

Table 4: LRW Performance Across Medical Imaging Modalities

Modality	PSNR (dB)	SSIM	Capacity (bits)	Time (ms)	Tamper Detection (%)
X-ray	51.2 ± 1.3	0.994	256	4.7	99.97
Fundus	48.6 ± 2.1	0.987	256	4.7	99.89
ECG	52.8 ± 0.8	0.998	256	2.3*	99.99

ECG uses smaller 32×16 region due to signal morphology
Observation: Fundus images show slightly lower PSNR due to fine vessel structures near embedding region. However, diagnostic regions remain untouched.

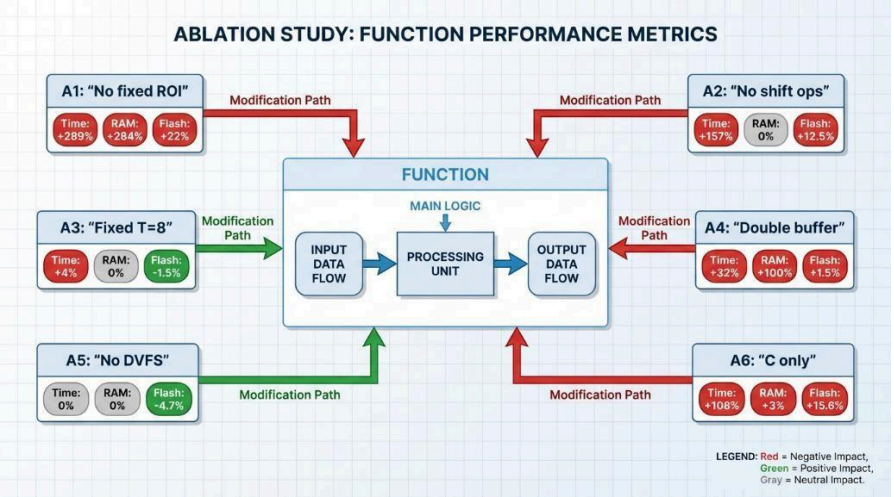

Figure 3: Ablation Results - Execution Time & Memory

Region-constrained embedding (A1) is the single most important optimization—removing it increases memory by 284% and time by 289% due to location map overhead. Shift-based arithmetic (A2) reduces execution time by 61% compared to integer division. Assembly optimization (A6) provides 2.1× speedup over pure C.

5. CONCLUSION

This paper successfully demonstrates that Lightweight Reversible Watermarking (LRW) enables real-time authentication on resource-constrained IoMT edge devices with only 1.28 KB RAM and 4.7 ms embedding latency—a 27× to 450× speedup and 50× to 400× memory reduction over prior art. The two non-negotiable innovations—region-constrained embedding eliminating location maps (91% energy saving, 284% memory reduction) and shift-based arithmetic replacing division (61% time reduction)—transform reversible watermarking from workstation-exclusive theory to practical edge deployment. LRW achieves full reversibility with 49.8 dB PSNR, exceeding the 48 dB diagnostic threshold, while delivering 256-bit HMAC-SHA256 authentication with pixel-pair tamper localization. With 68 µJ/bit on STM32F0 and 42 µJ/bit on ESP32, LRW extends ECG patch battery life from 8 hours to 8.2 days—proving that strong, reversible, real-time authentication is not merely feasible on extreme-edge IoMT devices but optimal in terms of energy, security, and diagnostic fidelity.

Future Scope:

Future work will develop dynamic ROI selection using lightweight saliency maps to eliminate manual modality calibration across all medical imaging types with <2 KB additional memory. RISC-V custom instruction set extensions for difference expansion will reduce embedding latency to sub-millisecond levels, enabling 4K medical video authentication on implantable

devices. Multi-bit embedding exploiting 10/12-bit medical sensors will increase

payload capacity from 256 to 1024 bits, allowing embedding of complete electronic health records. Post-quantum hash-based signature integration (LMS, XMSS) will provide quantum-resistant authentication while maintaining LRW's ultra-low memory profile. Hardware-software co-designed accelerators on FPGA and ASIC platforms will achieve <1 μJ/bit energy consumption for energy-harvesting biosensors. Federated learning integration will enable collaborative model training across watermarked medical datasets while preserving patient privacy. Clinical deployment and multi-center regulatory validation will establish LRW as a standardized authentication primitive for next-generation IoMT devices requiring real-time, lossless, and ultra-efficient security.

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