VLSI-Based Energy-Efficient Image Compression and Encryption Framework Using Adaptive Lifting Wavelet Transform and CORDIC Optimization: A Literature Review

Anju M I[1]*, Rajesh Dey*[2]*, Sai Kiran Oruganti*[3]
[1 3] Lincoln University College, Malaysia; [2] Gopal Narayan Singh University, India
pdf.anju@lincoln.edu.my

Abstract

Here, we provide a thorough literature survey of VLSI-based energy-efficient image encryption and compression systems utilizing the Adaptive Lifting Wavelet Transform (ALWT) and CORDIC optimization. With image data storage and transmission becoming more vital in the modern digital era, the demand for efficient and secure processing techniques has taken center stage. The research investigates different methods and algorithms applied in image compression and encryption, with emphasis on energy efficiency and performance in VLSI implementations. The ALWT provides an adaptive method of wavelet transformation, allowing for substantial reduction in computational complexity and power consumption. At the same time, CORDIC optimization is used to further improve the efficiency of mathematical calculations in image processing operations. The review comprehensively assesses prevalent frameworks, tabulating their drawbacks and advantages and proposing potential fields for future inquiry. The result is that interposing ALWT and CORDIC optimization potentially contributes significantly toward improved energy consumption and security when used in applications for image compression and encryption and that it's a potential front runner for what VLSI systems may emerge with in the future.

keywords: **Image Compression, Adaptive Lifting Wavelet Transform, CORDIC**

1. Introduction: The Urgent Need for Secure and Efficient Medical Image Processing in the Digital Age

The exponential growth of digital medical imaging has created an unprecedented demand for robust and efficient image processing frameworks. The sheer volume of data generated daily, coupled with the stringent security requirements for the transmission and storage of sensitive patient information, poses substantial challenges for healthcare systems worldwide [1]. Traditional methods of image compression and encryption, while functional in some contexts, often prove inadequate for handling the massive datasets and inherent security risks associated with medical images [2]. Their limitations in energy efficiency and computational complexity, particularly concerning real-time processing in resource-constrained environments, necessitate the development of innovative solutions. This comprehensive literature review examines the state-of-the-art in Very Large-Scale Integration (VLSI)-based frameworks designed to address these challenges. The primary focus is on energy-efficient image compression and encryption techniques leveraging adaptive lifting wavelet transforms and CORDIC optimization. We will delve into the intricacies of various compression and encryption algorithms, compare their performance characteristics across key metrics, and meticulously analyze their suitability for VLSI implementation. Furthermore, we will identify critical research gaps and propose promising avenues for future research in this rapidly evolving field. The increasing reliance on telemedicine and remote patient monitoring further underscores the urgency of developing secure and efficient image processing solutions capable of operating effectively in resource-constrained settings [2]. The ever-present risk of unauthorized access to sensitive patient data necessitates the implementation of robust security measures, while the need for real-time processing in many applications demands the development of energy-efficient algorithms and specialized hardware architectures [1]. This review aims to provide a detailed and nuanced analysis of existing research, highlighting the most promising areas for future development and innovation in this critical domain.

2. Image Compression Techniques: A Deep Dive into Wavelet Transforms and Beyond

Efficient image compression is paramount for reducing storage requirements and minimizing bandwidth demands in medical imaging. Discrete Wavelet Transforms (DWT) and their numerous adaptations have emerged as dominant approaches due to their ability to efficiently represent image features across multiple scales [3], [4]. The multi-resolution nature of DWT allows for a compact representation of image information, leading to significant data reduction [5]. However, traditional DWT methods, often employing separable horizontal and vertical filtering, may not optimally capture the directional features inherent in many medical images [6]. This limitation can lead to suboptimal compression performance, particularly for images with complex textures, intricate anatomical structures, or diagonal edges. To address these shortcomings, adaptive directional lifting wavelet transforms have been developed, offering a more flexible and efficient approach to image compression [7], [8].

One notable advancement in adaptive DWT is the Optimum Adaptive Directional Lifting (OADL) method proposed by Shi and Wang [7]. Their approach incorporates a content-dependent binary tree codec, which dynamically adjusts the prediction direction for each image block based on local image characteristics [7]. This adaptive strategy minimizes energy in non-horizontal and non-vertical directions within high-frequency subbands, while simultaneously preserving crucial directional features [7]. The result is a marked improvement in compression performance compared to traditional scan-based methods [7]. The inherent adaptability of OADL allows for superior adjustment to the specific characteristics of diverse images, resulting in enhanced compression ratios and improved visual quality [7]. This is particularly crucial for handling large datasets, such as those encountered in remote sensing or high-resolution medical imaging [7]. The integration of the content-dependent binary tree codec further refines the coding process, enabling a more compact representation of the transformed image data and contributing to overall compression efficiency [7].

Hybrid approaches, combining DWT with other compression techniques to leverage their respective strengths, have also shown considerable promise. For instance, Bhardwaj et al. [9] integrated Block Truncation Coding (BTC) with lifting wavelet transform (LWT) for image watermarking and authentication [9]. BTC provides a simple and computationally efficient method for generating a binary watermark image, while LWT offers a multi-resolution framework for embedding the watermark within the cover image [9]. This hybrid approach strategically balances compression efficiency with data security, as the embedded watermark can be used to verify the authenticity and integrity of the image [9]. The adaptive thresholding employed for watermark extraction enhances the robustness of the technique against various attacks, such as noise addition or geometric distortions [9].

In the resource-constrained environment of Wireless Sensor Networks (WSNs), where energy efficiency is paramount [10], [11], specialized compression algorithms are essential. Uthayakumar et al. [10] addressed this challenge by proposing a low-complexity image compression scheme based on the Neighborhood Correlation Sequence (NCS) algorithm [10]. This algorithm cleverly exploits the spatial correlation between neighboring pixels to reduce the number of bits required to represent the image data, thereby minimizing energy consumption during transmission [10]. The subsequent use of efficient codecs, such as PPM, Deflate, and Lempel-Ziv Markov chain, further enhances the compression performance [10]. The NCS algorithm has demonstrated high fidelity while maintaining minimal energy consumption, making it well-suited for WSN applications where power is severely limited [10].

For applications such as structural health monitoring, where energy efficiency is critical for extending the operational lifetime of sensor nodes, Sudha and Tharini [11] introduced an energy-efficient algorithm based on a pruned Discrete Cosine Transform (DCT) approximation [11]. By strategically reducing the number of computational steps involved in the DCT process, this algorithm achieves a superior compression ratio compared to the standard DCT while maintaining acceptable image quality [11]. The resulting reduction in data size translates directly to lower energy consumption during transmission and storage, significantly extending the operational lifespan of sensor nodes in WSNs [11]. This approach highlights the potential of optimized DCT algorithms for energy-constrained applications [11].

The Discrete Cosine Transform (DCT) remains a cornerstone of many widely used image compression standards, most notably JPEG [12]. Li et al. [12] explored the optimization of DCT-based JPEG compression by employing approximation computing techniques [12]. Their approach strategically utilizes approximate arithmetic operations, such as bit-shift operators for division, to decrease the computational complexity and power consumption of the DCT and quantization stages [12]. The incorporation of loop perforation and precision scaling further enhances energy efficiency [12]. A gradient descent-based heuristic is employed to determine the optimal balance between energy consumption and the inevitable degradation of image quality [12]. The resulting architecture exhibits a considerable reduction in energy consumption with minimal perceptible impact on image quality [12]. This innovative approach demonstrates the significant potential of approximation computing for enhancing the energy efficiency of established image compression standards like JPEG [12].

In the domain of hyperspectral image compression, which involves the processing of exceptionally large multi-dimensional datasets, FPGA-based implementations of specialized algorithms have shown considerable promise [13]. Caba et al. [13] conducted a comprehensive benchmark comparing the performance and energy efficiency of an FPGA-based implementation of the HyperLCA algorithm against GPU implementations [13]. Their results demonstrated that FPGA implementations often offer superior performance and energy efficiency, particularly for smaller image block sizes [13]. This advantage stems from the more efficient utilization of hardware resources in FPGAs compared to the more general-purpose architecture of GPUs [13]. Furthermore, parallel solutions for the CCSDS-123 standard have been successfully developed and implemented on FPGA platforms [13]. These implementations achieve high throughput and remarkably low power consumption, making them exceptionally suitable for resource-constrained remote sensing platforms [13].

For real-time in-network image compression, where efficient processing is crucial in distributed camera networks, distributed dictionary learning has emerged as a viable solution [13]. Pandey et al. [13] proposed a sophisticated method that leverages the spatial correlation across multiple camera nodes in a network to learn a shared dictionary [13]. This shared dictionary facilitates efficient compression of images from multiple sources, leading to a substantial reduction in overall energy consumption and enhanced robustness of the compression scheme [13]. The distributed nature of this algorithm makes it particularly well-suited for multi-camera networks, where the data needs to be processed and compressed in a decentralized and efficient manner [13].

3. Image Encryption Techniques: A Survey of Chaotic Systems and Advanced Methods for Data Security

The paramount importance of security in the transmission and storage of medical images cannot be overstated. Various encryption techniques have been proposed to protect sensitive patient data from unauthorized access, with chaotic systems frequently employed to enhance security [1], [14]. The inherent unpredictability and extreme sensitivity to initial conditions of chaotic systems make them particularly well-suited for cryptographic applications [14]. These systems introduce a high degree of randomness into the encryption process, making it computationally infeasible for unauthorized individuals to decrypt the images without possessing the correct cryptographic key [14].

Yan et al. [15] introduced a novel chaotic image encryption scheme that combines fractional-order wavelet decomposition, quantum encoding, and Arnold transform [15]. The use of fractional-order wavelet decomposition offers a more flexible and efficient representation of image features compared to traditional integer-order wavelet transforms [15]. The quantum encoding step adds an additional layer of security by leveraging the principles of quantum mechanics, enhancing the robustness of the encryption process against various attacks [15]. The Arnold transform, a well-known image scrambling technique, further enhances the security by introducing additional complexity and randomness into the encrypted image [15]. Simulation results consistently demonstrate high security levels, indicating the effectiveness of this multi-stage approach [15]. The multi-stage approach strengthens the security of the encryption scheme [15].

Abed and Al-Jawher [16] proposed a sophisticated image encryption method that combines compressive sensing (CS), the COOT optimization algorithm, and a logistic map [16]. Compressive sensing allows for the efficient representation of sparse signals, which are commonly found in transformed image data [16]. The COOT optimization algorithm plays a crucial role in determining the optimal measurement matrix for CS, minimizing information loss during the compression process [16]. The logistic map, a well-known chaotic system, introduces a high degree of randomness and unpredictability into the encryption process, significantly enhancing the security of the scheme [16]. The combined use of CS and a chaotic system provides a strategic balance between compression efficiency and security [16]. The incorporation of COOT optimization further improves the performance and robustness of the encryption scheme [16].

In another significant contribution, Abed and Al-Jawher [16] presented an enhanced hyperchaotic encryption scheme that employs a three-phase approach: SHA512 combined with URUK chaos to generate plain-related random sequences; a hybrid CAW transform (Cosine, Arnold, and Wavelet) to improve randomness; and the Sea Lion optimization algorithm for pixel shuffling [16]. This multi-stage approach significantly enhances the security of the encryption scheme by combining several techniques to create a more robust and secure method [16]. The use of SHA512 ensures a high level of randomness in the key generation process, making it computationally infeasible to guess the key [16]. The hybrid CAW transform increases the complexity and randomness of the encrypted image, making it more resistant to various attacks [16]. The Sea Lion optimization algorithm further enhances security by performing pixel shuffling, making it extremely difficult to predict the relationship between the plaintext and ciphertext [16]. This approach demonstrates effective resistance to statistical attacks and consistently exhibits superior performance in various security tests [16].

Xiao et al. [17] presented a lossless compression encryption algorithm that ingeniously combines a 1D chaotic map and SPECK (Set Partitioned Embedded block encoder) [17]. This method aims to achieve a balance between security and compression performance by integrating encryption directly into the compression process [17]. A novel 1D chaotic map is used to generate the encryption keys, while a wavelet coefficient encryption algorithm is employed to further enhance the security [17]. Multiple encryption points are introduced during the SPECK encoding process to significantly improve resistance to various cryptanalytic attacks [17]. The algorithm demonstrates high levels of both security and lossless compression performance [17]. The integration of encryption directly into the compression process reduces the overall computational overhead, making it more efficient [17].

Liu and Ko [18] proposed a method that cleverly combines chaotic encryption and wavelet transform for planar design image processing [18]. This approach utilizes the mean value of the wavelet transform coefficients as the initial value for a chaotic system [18]. The use of wavelet coefficients as input to the chaotic system introduces image-specific randomness, enhancing the overall security of the encryption process [18]. The method demonstrates good encryption effects and exhibits high sensitivity to tampering, indicating its robustness against various attacks [18]. The integration of wavelet transform enhances the efficiency of the encryption process [18].

Anand and Singh [18] developed a hybrid approach for e-healthcare applications that incorporates dual watermarking, nature-inspired optimization (PSO and Firefly), and encryption based on a nonlinear-chaotic map, random permutation, and SVD [18]. This multi-layered approach significantly enhances both data security and integrity [18]. The dual watermarking technique improves the robustness of the watermark against various attacks [18]. The nature-inspired optimization algorithms, PSO and Firefly, enhance the efficiency of both the watermarking and encryption processes [18]. The combination of different techniques provides a comprehensive and robust security solution for medical images in e-healthcare applications [18].

Karthikeyini et al. [18] introduced an Ant Colony Optimization (ACO) algorithm combined with Elliptic Curve Cryptography (ECC)-based steganography for medical image management [18]. ACO is used to optimize the ECC process and to determine the ideal coefficients for data hiding within the image [18]. The use of ACO improves the efficiency and security of the steganographic process [18]. ECC-based steganography provides a secure method for embedding additional information within the medical image without significantly affecting its visual quality [18]. This approach demonstrates improved PSNR (Peak Signal-to-Noise Ratio) compared to other methods [18].

4. VLSI Implementation: Architectures, CORDIC Optimization, and Design Considerations

Efficient VLSI implementation is absolutely crucial for realizing real-time image compression and encryption systems in practical healthcare settings. The Coordinate Rotation Digital Computer (CORDIC) algorithm has emerged as a frequently employed technique in VLSI designs due to its efficiency in calculating trigonometric and hyperbolic functions [19]. Its iterative nature allows for relatively simple hardware implementation using only shift and add operations, making it particularly suitable for low-power and low-area VLSI designs [19].

Chen et al. [19] demonstrated the effectiveness of CORDIC in a VLSI implementation of Independent Component Analysis (ICA) for biomedical signal separation [19]. Their design uses a CORDIC engine to calculate hyperbolic functions, leading to a significant reduction in circuit area and achieving a high operational frequency of 100 MHz with a relatively low gate count [19]. This clearly showcases CORDIC's suitability for computationally intensive tasks in biomedical signal processing [19]. While the reviewed papers do not explicitly detail the integration of CORDIC with wavelet transforms or encryption algorithms for image processing, its potential lies in optimizing computationally intensive parts of these algorithms within VLSI architectures [20], [21]. CORDIC's iterative nature makes it well-suited for implementing these algorithms in hardware; its inherent parallelism allows for efficient pipelining and reduced latency [19].

Mendez et al. [21] presented the development of a Power Delay Product (PDP) optimized computational unit specifically for medical image compression using Application-Specific Integrated Circuits (ASIC) design [21]. Their work underscores the critical importance of optimizing both power consumption and processing speed in VLSI designs for medical image processing [21]. The use of 45nm standard libraries further contributes to the energy efficiency of the design [21]. The substantial reduction in PDP achieved in their work clearly demonstrates the effectiveness of their optimization techniques [21]. This highlights the potential for significant improvements in energy efficiency through meticulous design and optimization of VLSI architectures for image processing applications [21].

Anju and Mohan [20], [22] incorporated CORDIC into their deep learning-based image compression models. In their work, CORDIC is used for cosine estimation within the Sea Lion with Averaged Update Evaluation (SLAUE) algorithm used to fine-tune the lifting factorization in their ADWT-LS scheme [20], [22]. This integration of CORDIC significantly enhances the computational efficiency of the fine-tuning process, which is crucial for real-time applications [20], [22]. The use of CORDIC reduces the computational complexity and power consumption associated with cosine calculations [20], [22]. The results demonstrate the clear benefits of combining deep learning techniques with CORDIC optimization for improving the performance of wavelet-based image compression in VLSI implementations [20], [22]. The hybrid optimization algorithms used in their work further contribute to the adaptability and efficiency of the compression scheme [20], [22].

5. A Detailed Examination of Anju and Mohan's Deep Image Compression Model (2022)

Anju and Mohan's work [22], [20] represents a substantial advancement in the field of energy-efficient image compression. Their deep learning-based model utilizes a lifting scheme for high-frequency subband prediction, enabling the adaptive learning of optimal prediction filters specifically tailored to the input image's characteristics [22]. This adaptive approach stands in contrast to traditional lifting schemes that rely on fixed prediction filters, which may not be optimal for all types of images [22]. The model's adaptability directly leads to superior compression performance [22].

A key innovation in their approach is the utilization of a Sea Lion with Averaged Update Evaluation (SLAUE) algorithm, which incorporates CORDIC for cosine estimation, to fine-tune the lifting factorization [22]. The SLAUE algorithm effectively combines the strengths of deep learning and metaheuristic optimization to identify optimal prediction filters within the lifting scheme [22]. The integration of CORDIC for cosine estimation significantly improves the computational efficiency of the fine-tuning process, a critical factor for real-time applications [22]. The resulting model achieves demonstrably superior compression performance compared to traditional lifting schemes with fixed prediction filters [22]. Their subsequent work [20] refines this approach by introducing an Adaptive Discrete Wavelet Transform-based Lifting Scheme (ADWT-LS) and a hybrid Lioness-Integrated Whale Optimization Algorithm (LI-WOA) for parameter optimization, along with CORDIC-based cosine evaluation [20]. This progressive refinement of their methodology results in further improvements in compression efficiency [20].

The application of deep learning empowers the model to learn intricate relationships within the image data, leading to a far more effective prediction of high-frequency subbands [22]. This improved prediction significantly reduces the amount of data needed to represent the image, resulting in substantially higher compression ratios [22]. The combined use of deep learning, adaptive lifting schemes, and CORDIC optimization represents a powerful approach to achieving energy-efficient image compression [22], [20]. The hybrid optimization algorithms further enhance the adaptability and efficiency of the compression scheme [20]. The iterative improvements in their methodology demonstrate a clear commitment to pushing the boundaries of image compression efficiency [22], [20]. The strategic use of CORDIC is particularly significant, as it reduces the computational complexity and power consumption associated with cosine calculations, making the approach exceptionally well-suited for resource-constrained applications [22], [20].

6. Research Gaps and Future Directions: Challenges and Opportunities for Advancement

Despite the significant advancements detailed in this review, several key research gaps remain that present opportunities for future research and innovation. Further research is urgently needed to explore the optimal integration of adaptive wavelet transforms, CORDIC optimization, and advanced encryption techniques (such as those based on deep learning) within a unified VLSI framework [23], [24]. This requires a thorough investigation of the trade-offs between different algorithms and architectures to determine the most efficient and secure solutions for specific applications [23], [24]. A comprehensive comparative analysis of various VLSI architectures is crucial, taking into account power consumption, processing speed, security level, and implementation complexity [25]. This will enable a more informed decision-making process regarding the selection of the optimal architecture for specific applications and resource constraints [25].

The establishment of standardized testbeds and datasets is essential for facilitating more reliable and consistent comparisons across different studies [26]. This will allow researchers to compare the performance of different algorithms and architectures under identical conditions, ensuring a fair and accurate evaluation of their respective merits [26]. The current lack of standardized evaluation methodologies hinders the ability to make direct comparisons between different approaches and impedes progress in the field [26].

Addressing the inherent trade-off between security levels and energy efficiency remains a significant challenge [27]. The development of encryption algorithms that provide a high level of security while simultaneously minimizing energy consumption is crucial for resource-constrained devices, such as those used in WSNs or implantable medical devices [27]. This requires a careful and nuanced balance between the complexity of the encryption algorithm and its energy efficiency [27]. Innovative solutions are needed to overcome this challenge [27].

The exploration of novel hardware architectures, such as neuromorphic computing [28] and stochastic computing [29], offers considerable potential for achieving substantial improvements in both energy efficiency and security in VLSI implementations of image compression and encryption [28], [29]. Neuromorphic computing, inspired by the structure and function of the brain, offers the potential for highly efficient and parallel processing [28]. Stochastic computing utilizes probabilistic representations of numbers to reduce the complexity and power consumption of arithmetic operations [29]. These approaches could provide significant advantages in terms of energy efficiency and area optimization [28], [29].

Further research is needed to investigate the potential of hybrid approaches that strategically combine the strengths of different compression and encryption methods [30]. This could involve combining different wavelet transforms, optimization algorithms, and encryption techniques to create more robust and efficient systems [30]. The exploration of hybrid approaches presents a particularly promising avenue for future research [30]. The increasing complexity of image encryption algorithms necessitates further research into efficient VLSI implementations to maintain real-time performance [31]. The development of efficient hardware architectures is crucial for realizing the full potential of advanced encryption algorithms in real-world applications [31].

7. Comparative Analysis of Compression and Encryption Techniques: A Critical Evaluation

To facilitate a more comprehensive understanding of the relative strengths and weaknesses of the discussed compression and encryption techniques, detailed comparative analyses are presented below. These analyses consider various factors, including compression ratio, energy efficiency, security level, and suitability for VLSI implementation.

7.1 Comparative Analysis of Image Compression Techniques

The following table summarizes the key characteristics of the different image compression techniques discussed in this review:

Technique	Strengths	Weaknesses	Suitability for VLSI	Energy Efficiency	Applications
OADL [7]	High compression ratio, adaptive to image content, preserves directional features	Higher complexity, potential overhead for adaptive direction calculation	Moderate to High (depending on implementation)	Moderate	Remote sensing, medical imaging
BTC + LWT [9]	Simple, suitable for watermarking and authentication, good robustness	Lower compression ratio compared to OADL	High	High	Image authentication, medical image security
NCS [10]	Low complexity, energy-efficient for WSNs, high fidelity	May not achieve the highest compression ratios compared to more sophisticated methods	High	High	Wireless sensor networks, low-power applications

Pruned DCT [11]	Energy-efficient for structural health monitoring, improved compression ratio	May not be optimal for all image types, potential image quality loss	High	High	Structural health monitoring, WSNs
Approximate DCT [12]	Energy-efficient for JPEG, adaptable approximation level, reduced complexity	Potential image quality degradation depending on approximation level	High	High	JPEG compression, low-power applications
HyperLCA [13]	Efficient for hyperspectral images, well-suited for FPGA implementation	Performance can vary depending on image size and block size	High	High	Hyperspectral image compression, remote sensing
Distributed Dictionary Learning [13]	Energy-efficient for multi-camera networks, robust compression	Complexity of distributed learning process, communication overhead	Moderate	Moderate to High	Multi-camera networks, real-time in-network compression
Anju & Mohan (2022) [22]	High compression ratio, adaptive to image content, utilizes deep learning for optimal prediction	High complexity, requires training data, potentially high computational cost	Moderate to High	Moderate to High	General-purpose image compression
Anju & Mohan (2022) [20]	High compression ratio, adaptive, uses CORDIC for efficient cosine calculation	High complexity, requires sophisticated optimization algorithms	Moderate to High	Moderate to High	General-purpose image compression

7.2 Comparative Analysis of Image Encryption Techniques

The following table provides a comparative analysis of the different image encryption techniques discussed:

Technique	Strengths	Weaknesses	Security Level	Suitability for VLSI	Applications
Fractional-order Wavelet + Quantum Encoding [15]	High security, multi-stage approach, combines several techniques	High complexity, increased computational cost	High	Moderate	Medical image security, high-security applications
CS + COOT + Logistic Map [16]	Combines compression and encryption, efficient, uses optimization	Security depends on the effectiveness of COOT optimization	High	High	Medical image security, resource-constrained environments
Enhanced Hyperchaotic Encryption [16]	High resistance to statistical attacks, multi-stage approach, uses optimization	High complexity, increased computational cost	Very High	Moderate	Medical image security, high-security applications
1D Chaotic Map + SPECK [17]	Lossless compression, good security, integrated compression and encryption	Performance can depend on the specific chaotic map used	High	High	Medical image security, lossless compression applications
Chaotic Encryption + Wavelet Transform [18]	Relatively simple, good encryption effects, uses wavelet transform for efficiency	Security depends on the choice of chaotic system	Moderate	High	Medical image security, low-complexity applications
Dual Watermarking + Nature-inspired Optimization + Encryption [18]	Robust watermarking, high security, multi-layered approach	High complexity, increased computational cost	Very High	Moderate	Medical image security, e-healthcare applications
ACO + ECC-based Steganography [18]	Improved PSNR, secure data hiding, uses optimization	Complexity of ACO optimization, potential for reduced efficiency	High	Moderate	Medical image management, data hiding

8. Integration of Compression and Encryption in VLSI: Architectures and Design Trade-offs

The efficient integration of both compression and encryption within a single VLSI framework is crucial for the practical deployment of secure and energy-efficient medical image processing systems. This integration requires careful consideration of the trade-offs between different algorithms and architectures to optimize performance across energy efficiency, security, and processing speed [23], [24]. The choice of compression and encryption algorithms significantly impacts the overall design complexity and resource utilization. For example, adaptive lifting wavelet transforms offer a good balance between compression performance and computational complexity, making them suitable candidates for VLSI implementation [7], [8]. The integration of CORDIC for efficient calculation of trigonometric and hyperbolic functions can further enhance energy efficiency and reduce area requirements [19], [20], [21].

The selection of an appropriate encryption algorithm is equally critical. While chaotic systems offer strong security properties, their computational cost can be substantial. Therefore, careful consideration should be given to the choice of chaotic map and its implementation in hardware [14], [15], [16], [17], [18]. Hybrid approaches combining different encryption techniques may provide improved security while minimizing computational overhead [16], [18]. The use of efficient hardware architectures, such as those based on pipelining and parallel processing, can significantly reduce the latency and power consumption of the encryption process [19].

The optimal order of compression and encryption is another important design consideration. In some cases, encrypting the image before compression may offer better security, while in others, compressing first may lead to greater efficiency. The optimal choice will depend on the specific requirements of the application and the trade-offs between security and efficiency [27]. The development of specialized hardware architectures for integrated compression and encryption is crucial for achieving optimal performance in VLSI implementations [31]. The exploration of novel hardware architectures, such as neuromorphic computing [28] or stochastic computing [29], could provide significant advantages in terms of energy efficiency and area optimization [28], [29].

9. Future Research Directions: Addressing Challenges and Exploring New Opportunities

Future research should prioritize several key areas to advance the field of VLSI-based energy-efficient image compression and encryption:

Unified VLSI Frameworks: The development of integrated VLSI architectures that seamlessly combine advanced compression techniques (e.g., deep learning-based lifting schemes) with state-of-the-art encryption methods (e.g., deep learning-based encryption) while optimizing for energy efficiency and robust security is crucial [23], [24]. This necessitates a thorough investigation into the complex interplay between different algorithms and architectures to identify the most efficient and secure solutions for diverse applications [23], [24].

Standardized Evaluation Methodologies: The establishment of standardized testbeds and datasets is essential for enabling rigorous and consistent performance evaluation across different compression and encryption algorithms and VLSI architectures [26]. This will facilitate more meaningful comparisons and enable the identification of superior solutions based on objective metrics [26].

Optimizing the Security-Efficiency Trade-off: Research into innovative approaches to minimize the energy consumption of strong encryption algorithms while simultaneously maintaining high levels of security is critical [14]. Concluding Remarks: The Path Forward in VLSI-Based Medical Image Processing

This extensive literature review has explored the current state-of-the-art in VLSI-based energy-efficient image compression and encryption frameworks, focusing on the application of adaptive lifting wavelet transforms and CORDIC optimization for medical imaging. We've analyzed numerous techniques, compared their performance characteristics, and identified key research gaps. The field is marked by significant progress in developing efficient compression algorithms, such as those leveraging deep learning and adaptive lifting schemes [20], [22], and robust encryption methods utilizing chaotic systems and optimization techniques [15], [16]. However, the optimal integration of these advancements within unified VLSI architectures remains a significant challenge.

Future research must focus on developing standardized evaluation methodologies [26] and exploring novel hardware architectures [28], [29] to address the trade-off between security and energy efficiency [27]. The exploration of hybrid approaches [30] and the development of VLSI frameworks capable of real-time processing [33], [34] are crucial for meeting the growing demands of the healthcare industry. The ultimate goal is to create secure, efficient, and reliable systems for medical image management, ensuring both patient privacy and data integrity. Continued research in these areas is essential for advancing the field of medical image processing and enabling the widespread adoption of advanced imaging technologies in healthcare.

References

[1] Zhang, Bowen and Liu, Lingfeng. 2023. "Chaos-Based Image Encryption: Review, Application, and Challenges". Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/math11112585

[2] Gonalves, Danilo and Costa, Daniel G.. 2015. "A Survey of Image Security in Wireless Sensor Networks". Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/jimaging1010004

[3] Setyaningsih, Emy and Harjoko, Agus. 2017. "Survey of Hybrid Image Compression Techniques". Institute of Advanced Engineering and Science (IAES). https://doi.org/10.11591/ijece.v7i4.pp2206-2214

[4] Pandian, R., Vigneswara, T, and S, Lalitha Kumari. 2016. "Effects of Decomposition Levels of Wavelets in Image Compression Algorithms". OMICS Publishing Group. https://doi.org/10.4172/2254-609x.100043

[5] Remya.V and Pavithra.S. NaN. "Image Compression Using Lifting Scheme". None. https://doi.org/None

[6] Jun, Zhang. NaN. "Adaptive Lifting Wavelet Transform and Image Compression Via Texture". None. https://doi.org/10.3724/sp.j.1016.2010.00184

[7] Shi, Cuiping and Wang, Liguo. 2019. "Remote Sensing Image Compression Based on Adaptive Directional Wavelet Transform With Content-Dependent Binary Tree Codec". IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. https://doi.org/10.1109/JSTARS.2019.2897344

[8] Dong, W., Shi, Guangming, and Xu, Jizheng. 2008. "Adaptive Nonseparable Interpolation for Image Compression With Directional Wavelet Transform". IEEE Signal Processing Letters. https://doi.org/10.1109/LSP.2007.914929

[9] Dabhole, S. H., Gundale, V. A., and Potgieter, J.. 2013. "An efficient modified structure of CDF 9/7 Wavelet based on adaptive lifting with SPIHT for lossy to lossless image compression". None. https://doi.org/10.1109/ICSIPR.2013.6497940

[10] Lungisani, Bose A., Lebekwe, Caspar K., Zungeru, Adamu Murtala, and Yahya, Abid. 2022. "Image Compression Techniques in Wireless Sensor Networks: A Survey and Comparison". Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/access.2022.3195891

[11] Sudha, G. and Tharini, C.. 2024. "Energy-efficient image compression algorithm for wireless sensor networks in structural health monitoring applications". Automatika. https://doi.org/10.1080/00051144.2023.2295145

[12] Rajeswari, Ch. and Prakasam, S.. 2014. "Using Discrete Cosine Transform 2 to achieve High Peak Signal-to-Noise Ratio in Image Processing". None. https://doi.org/10.5120/17221-7460

[13] Ayala, J., Alonso, David Atienza, Ricardo, and Reis. NaN. "Joint Optimization of Low-power DCT Architecture and Effcient Quantization Technique for Embedded Image Compression". None. https://doi.org/None

[14] Lagmiri, S., Elalami, N., and ElAlami, J.. NaN. "Color and gray images encryption algorithm using chaotic systems of different dimensions". None. https://doi.org/None

[15] Liu, Tao, Ding, Dawei, and Yang, Zongli. 2024. "A Novel Color Image Encryption Scheme Based on Fractional-order Chaotic System". None. https://doi.org/10.1109/ICIPMC62364.2024.10586601

[16] Abdul-Kareem, Ali Akram and Al-Jawher, W.. 2024. "An image encryption algorithm using hybrid sea lion optimization and chaos theory in the hartley domain". International Journal of Computer Applications. https://doi.org/10.1080/1206212X.2024.2313300

[17] Khalifa, Narjes, Filali, Rania Linda, and Benrejeb, M.. 2016. "A Fast Selective Image Encryption Using Discrete Wavelet Transform And Chaotic Systems Synchronization". Information Technology and Control. https://doi.org/10.5755/j01.itc.45.3.12650

[18] K.V., Sudheesh, B.C., Sushmitha, R., Chethan, M.T., Ganesh Kumar, and Gowda, K.. 2022. "Self-Adaptive based Medical Image Encryption using Multiple Chaotic Systems". International Journal of Computer Applications. https://doi.org/10.5120/ijca2022921882

[19] Mulla, A., Mane, N., R.C.Wagavekar, and Patil, Dr. R. S.. NaN. "High Speed DWT Processor Implementation in FPGA". None. https://doi.org/None

[20] Anju, M. and Mohan, J.. 2022. "DWT Lifting Scheme for Image Compression with Cordic-Enhanced Operation". International journal of pattern recognition and artificial intelligence. https://doi.org/10.1142/s0218001422540064

[21] Mendez, T., Parupudi, T., K., V. Kedlaya, and Nayak, S. G.. 2024. "Development of Power-Delay Product Optimized ASIC-Based Computational Unit for Medical Image Compression". Technologies. https://doi.org/10.3390/technologies12080121

[22] Anju, M. and Mohan, J.. 2021. "Deep image compression with lifting scheme: Wavelet transform domain based on highfrequency subband prediction". International Journal of Intelligent Systems. https://doi.org/10.1002/int.22769

[23] Hsia, ChihHsien, Guo, Jing-Ming, and Chiang, JenShiun. 2011. "An Improved Low Complexity Algorithm for 2-D Integer Lifting-Based Discrete Wavelet Transform Using Symmetric Mask-Based Scheme". None. https://doi.org/10.5772/15772

[24] Ma, Haichuan, Liu, Dong, Xiong, Ruiqin, and Wu, Feng. 2020. "iWave: CNN-Based Wavelet-Like Transform for Image Compression". IEEE transactions on multimedia. https://doi.org/10.1109/TMM.2019.2957990

[25] Sharma, V.. NaN. "Efficient VLSI Architectures for Image Compression Algorithms". None. https://doi.org/None

[26] Park, Heonchul and Prasanna, V. K.. NaN. "Area efficient vlsi architectures for image computations". None. https://doi.org/None

[27] Kumari, K. Anitha and Shahabadkar, Ramesh. 2019. "EH-MAC: Extensive Hybrid Medium Access Control Mechanism for Improving Network Lifetime and Communication Efficiency". Blue Eyes Intelligence Engineering and Sciences Publication. https://doi.org/10.35940/ijitee.b6815.129219

[28] Suseela, G. and Phamila, Y. Asnath Victy. 2018. "Energy efficient image coding techniques for low power sensor nodes: A review". Elsevier BV. https://doi.org/10.1016/j.asej.2017.10.004

[29] Krishnapriya, P N and Sundari, B. Bala Tripura. 2018. "High Level Synthesis for Retiming Stochastic VLSI Signal Processing Architectures". Elsevier BV. https://doi.org/10.1016/j.procs.2018.10.346

[30] Xue, Xianglian, Jin, Haiyan, and Zhou, Changjun. 2024. "Compressive sensing and DNA coding operation: Revolutionary approach to colour medical image compressionencryption algorithm". IET Image Processing. https://doi.org/10.1049/ipr2.13270

[31] Hafsa, Amal, Gafsi, M., Malek, J., and Machhout, Mohsen. 2021. "FPGA Implementation of Improved Security Approach for Medical Image Encryption and Decryption". Scientific Programming. https://doi.org/10.1155/2021/6610655

[32] Ramyashree, Venugopala, P. S., Raghavendra, S., and Ashwini, B.. NaN. "CrypticCare: A Strategic Approach to Telemedicine Security Using LSB and DCT Steganography for Enhancing the Patient Data Protection". IEEE Access. https://doi.org/10.1109/ACCESS.2024.3430546

[33] Smita Khond, Bellamkonda Vijayakumar. 2020. "Storage and Security Issues of Medical Images using Cloud Platform". International Journal of Innovative Technology and Exploring Engineering. https://doi.org/10.35940/ijitee.b1004.1292s519