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Original Article

Real-Time Adaptive Rate Control for Hyperspectral Image Compression on FPGA

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Abstract - *The spectral analysis capabilities of Hyperspectral imaging produce large datasets that create problems when storing and transmitting the data, along with processing it in real-time. Traditional compression approaches that use transform-based and deep learning methods either need versatile adaptation features or considerable computational power. A real-time adaptive rate control hyperspectral image compression system based on FPGA and software co-design features the proposal. The proposed method optimizes compression efficiency through three elements, which include adaptive quantization and entropy coding and a dynamic rate control system. The method processes hyperspectral data at speeds faster than 25 frames per second while using less than 5 watts of power to deliver compression ratios between 10:1 and 50:1 and PSNR values from 35-45 dB, along with SSIM measures between 0.92 and 0.98. The approach achieves a lower bit rate level of 30–50% when compared to earlier research methods while delivering superior visual results. The proposed solution delivers an effective power-saving method for real-time hyperspectral image compression, which benefits satellite and UAV applications.*

Keywords - *Field-Programmable Gate Array, Structural similarity index, Unmanned aerial vehicle, Airborne visible/infrared imaging spectrometer, Hyperspectral digital imagery collection, Rate-distortion optimization Experiment, Band sequential.*

1. Introduction

Hyperspectral imaging has stood out in recent years because it delivers precise information regarding wavelengths combined with spatial data throughout a broad spectrum. The extensive capability of hyperspectral sensors to measure hundreds of band segments differentiates them from standard imaging systems that acquire the RGB spectrum because this bandwidth allows for exact material detection and classification [1]. This technology applies to remote sensing as well as environmental monitoring services while simultaneously benefiting medical imaging practice and precision agriculture operations, together with military surveillance applications [2]. Hyperspectral imaging faces its main difficulty because sensor-generated data volumes become overwhelmingly large, which directly impacts storage needs, increases computational requirements, and data transmission requirements. Real-time processing and transmission of hyperspectral images requires effective compression methods because resource-limited satellite and UAV-based systems demand this capability [3]. The literature showcases various techniques for compressing hyperspectral images, which include transform-based and predictive methods and approaches based on machine learning. Hyperspectral data compression methods that preserve perfect image fidelity, such as Huffman coding, arithmetic coding, and predictive coding, prove insufficient when compressing highly related hyperspectral information because they do not produce notable compression efficiency improvements [4]. The combination of Discrete Wavelet Transform (DWT) with Karhunen–Loève Transform (KLT), along with JPEG2000, provides effective decorrelation of hyperspectral images that ultimately results in superior compression efficiency rates [5]. These compression techniques use too much processing power and cannot be used in real-time systems. Hyperspectral imaging has become a very effective tool in remote sensing because it is able to record a large amount of spectral data in hundreds of thin bands. Nevertheless, real-time processing, transmission, and storage are, in any case, bottlenecked by the sheer strength of hyperspectral sensor output, especially in cases where satellite and UAV technologies have limited computer and energy resources. The current techniques, like deep learning and transform-based, are either computationally expensive or fail to adjust to dynamic conditions. That leaves a research gap: there is a need for a real-time, low-power, adaptive coding scheme with the capability of bandwidth-aware rate control. In this regard, the proposed work proposes an adaptive rate control mechanism on an FPGA that dynamically manipulates compression in reaction to the system constraints. This system would bridge that technological gap between software's high accuracy and hardware without flexibility at runtime systems that exists today. Deep learning-based compression techniques currently lead to the best compression ratios and reconstruction quality possible. The compression of hyperspectral images benefits from the use of three main neural network approaches, including autoencoders and Convolutional Neural Networks (CNNs) with deep recurrent models [6]. The successful operation of deep learning-based compression methods exists within strict restrictions since it demands large processing capabilities with substantial datasets, which render them unusable in satellite board environments [7]. The majority of compression methods currently used do not have adaptive rate control features that enable bandwidth adaptation during real-time transmission processes. Nevertheless, most of the techniques do not offer the dynamic rate control feature, and do not work well when faced with the variations in the bandwidth and cannot be used in real-time and resource-constrained platforms. Such constraints emphasize the necessity of such a solution that is soft on power with an adaptive compression rate that can be varied on-the-fly, and yet the quality of the image is desirable under the constrained environment.

Previous works suffer from an essential weakness because they lack hardware-efficient implementations. The high power consumption of GPUs makes them ineffective for power-sensitive applications since they require significant energy to offer their processing speed. The sequential execution design of CPUs makes them incapable of reaching real-time processing speeds. Field-Programmable Gate Arrays (FPGAs) present themselves as a suitable solution for hyperspectral image compression in real time because they offer low latency and parallel computing as well as reconfiguration capabilities [8]. Most FPGA-based implementations described in the literature depend on fixed-rate compression techniques that fail to dynamically optimize bandwidth utilization. An adaptive framework for efficient hyperspectral image compression must be developed because of existing challenges to achieve: The compression system should automatically modify its compression speed according to available system resources and network bandwidth. The system should manage both exceptional image quality and substantial data compression results [9]. An FPGA acceleration system enables time-responsive operation along with low-power utilization for processing [10]. The system supports effective data hyperspectral transfer and storage capabilities in resource-limited platforms, including satellite and UAV systems, as well as edge devices. The objective comes from the pitfalls of fixed-rate compression in bandwidth optimization and the high computational resource needs of deep learning compression techniques [11]. The proposed method integrates adaptive compression's beneficial properties with FPGA hardware speedup for creating a practical system that handles real-time hyperspectral image processing. A real-time adaptive rate control framework that serves as an improvement to existing hyperspectral image compression methods through hardware-software co-designed solutions [12]. It contains the following particular goals: The goal is to create and execute a real-time FPGA-based hyperspectral image compression system that uses system constraints as inputs to modify compression rates dynamically [13]. An adaptive rate control system needs development for finding the optimal balance among compression ratio, image quality and transmission bandwidth levels. Hooking up hardware-based compression capabilities like DWT, adaptive quantization and entropy coding into an FPGA system architecture [14]. The proposed approach requires evaluation through measurement of compression ratio together with Peak Signal-to-Noise Ratio (PSNR), Structural Similarity Index (SSIM), processing speed and power consumption levels [15]. The proposed method will be tested against current compression techniques to demonstrate its superior compression speed and real-time operation capabilities.

A new adaptive quantization together with an entropy coding mechanism controls compression rates in real-time based on the operating system requirements [16]. The integration of an embedded processor with an FPGA-based parallel processing unit enables real-time hyperspectral image compression that operates efficiently through minimal latency [17]. The proposed system maintains PSNR levels above 35 dB with SSIM scores greater than 0.92 yet achieves 30–50% better data compression efficiency than static compression methods [18]. The FPGA-based processing method delivers real-time data compression at 5W power use, which surpasses GPU implementations with their substantial energy consumption [19]. The proposed method receives evaluation using actual hyperspectral datasets, which include AVIRIS and HYDICE, while conducting a comparative study with leading compression techniques developed [20]. New learning-based compressive techniques combined with optimized FPGA implementations represent the current work direction.

The following structure arranges the rest of this document: This section reviews recent hyperspectral image compression techniques and explores their current limitations, as it leads to the proposed approach [21]. The proposed real-time adaptive compression framework contains details about the hardware-software co-design strategy, FPGA implementation and adaptive rate control mechanism in Section 3. Section 4 outlines the experimental design that incorporates informative details about the datasets together with the evaluation metrics and the specific hardware specifications for the FPGA testing platform [22]. The findings alongside performance evaluations are disclosed in Section 5, where competitors' approaches are measured for data compression effectiveness and speed alongside electricity utilization and image quality metrics (PSNR, SSIM) [23]. It finishes by exploring potential avenues for additional investigation, which include adding machine learning adaptive compression methods alongside more FPGA performance enhancements [24]. Relative to remote sensing applications, hyperspectral images necessitate urgent compression solutions because they deal with excessive amounts of data and bandwidth restrictions alongside performance restrictions. Current compression systems exhibit two main shortcomings: using static compression rates, which are expensive to compute and producing suboptimal hardware designs [25]. The presented study develops a real-time adaptive compression system built around FPGAs, which dynamically controls compression rates for optimal efficiency and low latency with energy conservation. This approach solves major issues in hyperspectral image processing by delivering improved performance over existing methods regarding compression efficiency, along with increased processing speed and enhanced adaptability. However, the feature of dynamic rate control is not provided by the majority of the techniques, and they perform rather poorly when challenged with the fluctuations of the bandwidth, hence are not applicable in real-time and resource-constrained platforms. The need for such a solution that is soft on power with an adaptive compression rate that can be varied on-the-fly, but the quality of the image should be acceptable in a limited environment is stressed.

2. Literature Review

A novel hardware implementation of a lossy multispectral and hyperspectral image compressor for onboard operation in space missions. The compression algorithm extends the Consultative Committee for Space Data Systems (CCSDS) 123.0-B-1 lossless standard by adding a bit-rate control stage that allows managing losses during compression to achieve higher compression ratios while maintaining image quality [27]. HLS techniques enable design productivity growth through raised abstraction levels for implementing the algorithm. The lossy compression solution gets deployed onto ARTICo3 to deliver a runtime adaptive solution, which allows users to select a performance level by adding more hardware accelerators for enhanced throughput while also managing power usage and fault tolerance by using accelerator grouping to achieve hardware redundancy [26]. A Xilinx Zynq UltraScale+ Field-Programmable Gate Array (FPGA)-based MPSoC implements the testing of the complete compression solution with various input images ranging from multispectral to ultraspectral types. The proposed implementation on Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) images requires 36 seconds of execution time when eight accelerators operate at 100 MHz, since it utilizes 20% of LUTs and 17% of dedicated memory blocks in the target device [28]. The processing technique defines a 15.6× acceleration rate against a basic ARM Cortex-A53 processor implementation of the algorithm. Using lossless hyperspectral pictures reduces overall data size and results in lower storage and transmission costs. A dynamic pipeline hardware solution for JPEG2000 compression and decompression. The architecture design was developed to operate efficiently in Field Programmable Gate Array (FPGA) hardware units for image processing applications. Background pauses in the pipeline system prevent errors that occur when modifying coding parameters [29]. The implementation of Bit-plane coding reduced execution time for image coding operations, thereby speeding up parameter update processes. Through shorter contextual information and faster decision protocols, the system reached a higher processing speed. JPEG2000 compression/decompression hardware modules based on parallel block compression architecture produced systems with flexible block dimensions, along with enhanced compression/decompression capabilities, higher picture processing speed and reduced frame processing duration [30]. Results of verification emerged when the Zynq-7000 system-on-chip operated JPEG 2000 compression. The method provided lossless compression of hyperspectral picture cubes for satellite processing. The recommended design technique requires fewer resources while achieving better compression efficiency with increased clock speed than previously used methods. The implementation of hyperspectral image (HSI) classification remains the standard practice in remote sensing imagery analysis, where both high accuracy and quick processing speeds are necessary. It demonstrates that Convolutional Neural Network (CNN) methodologies presently represent the best technology for HSI classifications [32]. The numerous dimensions present in HSI create processing challenges for CNN models, so they cannot meet real-time response requirements when compared to SVMs and other traditional methods. Previous CNN implementations within HSI lacked design features that optimize their deployment on embedded FPGAs [33]. A new CNN-based systematic algorithm for HSI classification, which specifically considers efficiency implications during hardware implementation. The proposed algorithm obtains a customized architectural design that enables FPGA resource-based mapping to fulfill real-time onboard classification with minimal power demands. The accelerator implemented on a Xilinx Zynq 706 FPGA achieves greater throughput than 70 times the speed of an Intel Xeon CPU and 3 times the speed of an NVIDIA GeForce 1080 GPU. The proposed FPGA accelerator delivers equivalent processing speed compared to existing SVM-based systems, even though it reaches higher classification accuracy. The present sensor systems development trend aims to achieve improved precision with better resolution through smaller devices that require less power. FPGAs serve as specific reprogrammable hardware components that enable proper exploitation to generate a reconfigurable sensor system. The system benefits from adaptation capabilities, which allow developers to implement complex applications through partial reconfigurable features with minimal power usage. FPGAs have been preferred for intense applications because their design flexibility leads to high parallel processing capabilities and on-chip memory architectures, together with adaptable functionality, which results in exceptional algorithm development performance. Sensor system performance has improved through FPGA technology, which has produced rapid growth across new application areas. Spanish technology projects focus on generating smarter sensor systems with reconfigurable design capabilities at lower power levels based on FPGAs [34]. The document presents an overview of present-day developments, which includes a description of different FPGA technology utilization alongside projections for forthcoming studies. The hyperspectral image compression algorithm adopted by Consultative Committee for Space Data Systems (CCSDS) causes significant feedback-loop latency and sophisticated computational complexity when operating in Band Sequential (BSQ) and Band Interleaved by Line (BIL). A forward prediction method using Xilinx Inc.'s xc7k325tffg9000 field programmable gate array chip will short the feedback loop time delay by modifying the CCSDS algorithm computation sequence. Real-time data processing and dynamic image parameter configuration occurred after implementing full-pipeline construction on FPGA boards [35]. The optimized algorithm succeeds in reproducing original algorithm operations with minimal hardware demands at the speed-insensitive path, and the proposed method reaches 103MHz frequency speed with 1.237Gbps throughput when processing 12-bit input hyperspectral data. The advancement of hyperspectral sensors created an enlarged potential to gather better-quality data. Such data expansion necessitates the creation of innovative methods to advance the storage and transmission of large datasets to ground stations. Massive information processing requires the emerging approach of compressive sensing that obtains compressed signals directly instead of working with entire datasets. The technique lowers the quantity of data that needs to be recorded before transmission and storage. A hardware-testing combination using System-on-Chip (SoC) Field-Programmable Gate Array (FPGA) for compressive sensing implementation. An airborne visible/infrared imaging spectrometer sensor image with 512 lines, 614 samples and 224 bands operates the compressive sensing algorithm at a unitary compression rate in 0.35 seconds [36]. The proposed system achieves a runtime performance comparable to 49× faster than the embedded 256-core GPU of the Jetson TX2 board and 216× faster than the SoC FPGA ARM. The proposed system needs energy consumption 100 times lower than alternative solutions. The development of lossy compression methods has increased throughout the past decades because new-generation hyperspectral sensors generate a rapid increase in data rate; yet linear compression methods preserve unneeded data about unimportant areas of interest while lacking sufficient information about regions of investigation. The added runtime adaptive distortion to HyperLCA enables multiple compression ratios within the same operation. The solution maintains its FPGA-friendly characteristics because it adopts the same deployment methods found in its previous version, which simplifies hardware implementation on Field Programmable Gate Arrays [37]. The modified compressor completes processing of 1024 × 1024 hyperspectral images together with 180 spectral bands, 377.5 MB within 0.935 seconds at 1.145 W power consumption. The experimental findings demonstrate superior M Samples/s performance as well as MB/s/W energy-efficiency levels from the architecture, which exceeds the best available state-of-the-art measures by factors of 10× and 6× respectively. Different remote sensing applications require hyperspectral imaging technology, which proves to be expensive in terms of computational resources. The size of hyperspectral data creates challenges for its computational requirements and storage needs, which become more pronounced because of modern sensor advancements. The process of moving airborne satellite data to ground processing facilities encounters bandwidth problems alongside data transfer. Data processing capabilities become crucial for platforms that have limited power supply capacity, limited weight, and storage resources. Preserving hyperspectral picture information can be achieved through onboard data compression methods to address these issues. An extensive analysis of hyperspectral image compression techniques through hardware acceleration for remote sensing purposes. From 2000 to 2021, it examined 101 articles [38]. It analyzed how synthesized results measure their power usage together with their throughput capability and compression ratio capabilities. Among the most efficient methods, it ranks them, followed by an analysis that reveals essential elements controlling the performance of compression utilizing hardware acceleration. Remote sensing depends on the important technique known as hyperspectral imaging, with its capability to achieve high spectral resolution. Hyperspectral remote sensing missions, along with improved temporal resolution, lead to rising availability and increasing dimensions of hyperspectral data [39]. The efficient compression and interpretation of hyperspectral data through automated processing methods are needed for space-based imaging platforms because this reduces satellite-to-Earth connection demands and optimizes hyperspectral analysis operations across numerous usage domains. Field Programmable Gate Arrays (FPGAs) have emerged as the primary choice for remote sensing onboard processing during the previous year, owing to their diminished real estate requirements and power consumption that exceeds traditional high-performance computing systems and because FPGAs became more resilient to spaceborne ionizing radiation exposure [40]. The extensive literature base about FPGAs in remote sensing does not include a dedicated work discussing how this flexible technology applies to modern hyperspectral remote sensing processes. It begins this series of developments by delivering a substantial review that evaluates present and prospective FPGA and reconfigurable hardware applications in hyperspectral remote sensing missions.

The literature reviewed constitutes valuable knowledge on the topic of hyperspectral image compression, yet fails to offer a centralized discourse that can tie available solutions to the environment of the proposed system. The majority of works applied either to static-rate compression, transform-based approaches or deep learning technologies implemented on GPUs, skipping hardware-efficient real-time applications. An example is that JPEG2000 and CCSDS formats provide good compression, but they are unsuitable in real-time UAV missions since they are quite slow [41]. On the same note, CNN-based compression methods have higher accuracy than non-CNN-based methods, though they consume a lot of computation and will be unfeasible to implement in low-power devices. Adaptive frameworks are discussed in very few studies, and FPGAs are used in even fewer studies to achieve dynamic rate control. Such a lack of hardware-oriented adaptive compression, especially in real-time background, gives emphasis to the proposed solution. It extends into the foundation set by these previous methods with the flexibility of software connected to the efficiency of the FPGA. The proposed new method is unique in that it uses both hardware and software co-design approaches combined with hard-coded adaptive quantization and entropy coding, making it real-time, which has never been applied to hyperspectral image compression before, with hard constraints on the power and latency requirements. It contrasts with the previous efforts, which covered either fixed-rate compression or GPU/CPU-based systems that required excessive amounts of energy to execute. Unlike them, the given framework can dynamically adjust the level of compression depending on the bandwidth and image properties in real-time [26]. The comparative assessment with modern methods in 2022-2024 years of JPEG2000, hybrid transform coding, and deep learning-based CNN models has shown a higher by 3050%bit rate reduction, and PSNR improvement of 24 dB and SSIM enhancement of up to 0.07. These outcomes confirm the exclusivity and success of the solution towards realising scalable, efficient and adaptive compression that can be applied to next generations of satellite and UAV imaging platforms.

3. Proposed Work

3.1. Dynamic Hyperspectral Image Compression: An Adaptive Rate-Controlled FPGA Framework

3.1.1. Intelligent Compression Framework for Hyperspectral Imaging

Real-time applications require spectral and spatial information compression due to the high amount of data contained in hyperspectral images. The framework stimulates a compression method that uses dynamic rate-controlled procedures to meet different image quality requirements and bandwidth and storage specifications. The system delivers dynamic compression parameter adjustment in real-time because it differs from fixed-rate conventional methods. Adaptive control Feature of FPGA to address the drawbacks of other hyperspectral image compression systems utilizing CPUs and GPUs. The current methods rely on software-intensive architectures that consume too much power and cannot be readily responsive to real-time requirements in edge applications like satellites and UAVs. These systems usually fail to adapt parameters of compression to differentiated bandwidth and data limitations and end up in either inefficient data and image transmission or poor quality of the images. The proposed system contributes to advancing adaptive quantization and entropy coding into an open-source, lightweight FPGA framework, being highly efficient in terms of power consumption and speed as well as adaptability. The dynamic rate control achieved in this real-time compression ability holds high PSNR and SSIM values without overloading the hardware. Accordingly, the suggested framework addresses the gap that conventional systems could not manage and preconditions the scalable, low-power, high-performance hyperspectral image compression. The representation of a hyperspectral image appears as follows in Equation (1),

$$I \in R^{M \times N \times B} \tag{1}$$

The image consists of M and N spatial dimensions along with B spectral bands. The compression process follows in Equation (2),

$$C = E(Q(T(I))) \tag{2}$$

The system applies a transformation function $T(\cdot)$ using Discrete Wavelet Transform (DWT) together with Principal Component Analysis (PCA), while $Q(\cdot)$ performs adaptive quantization followed by entropy coding through $E(\cdot)$, which ultimately creates C as output.

3.1.2. Adaptive Quantization for Efficient Compression

The framework achieves its main innovation through adaptive quantization because it dynamically modifies quantization steps based on specific rate-distortion properties. The optimal quantization step Q finds its calculated through Equation (3),

$$Q = \frac{\sigma_B}{R_{target}} \tag{3}$$

The algorithm performs the calculation based on the standard deviation value of band B while considering the target bit rate R_{target}. The system provides an automatic adjustment capability that optimizes compression performance and image quality according to data changes.

3.1.3. FPGA-Optimized Hardware-Software Co-Design

The compression system has been implemented on Zynq-7000 SoC FPGA devices to attain real-time processing capabilities through parallel computation and hardware speedup. The FPGA-based architecture provides low power usage at less than 5W operation and enables minimal latency at about 40ms, along with processing speeds of 25+ FPS, surpassing CPU and GPU implementations. The coupling of adaptive rate control technology with an FPGA acceleration system creates an effective method for power-efficient hyperspectral image compression, which caters to remote sensing requirements alongside UAVs and satellite-based systems, as shown in Figure 1. The Predictor-Based Adaptive Compression System is essential because it optimizes hyperspectral image compression through real-time bit-plane prediction functions that wipe out redundancies and enhance transmission quality. The adaptive rate control module evaluates incoming hyperspectral images to determine their most essential spectral data. The system implements error detection through computational error methods to track variations between predicted and actual bit-planes and execute dynamic quantification changes. The quantization step adaptation element of the system regulates compression ratio performance through bandwidth availability and quality constraint feedback mechanisms. A reduced bitstream emerges from an entropy code process that reduces storage costs as well as transmission expenses. The system delivers superior spectral retention during compression processes when the compression ratio reaches between 10:1 and 50:1. The FPGA-based architecture allows real-time processing through this system, which produces faster data transmission and lower latency and is suitable for satellite imaging and UAVs, and remote sensing applications.

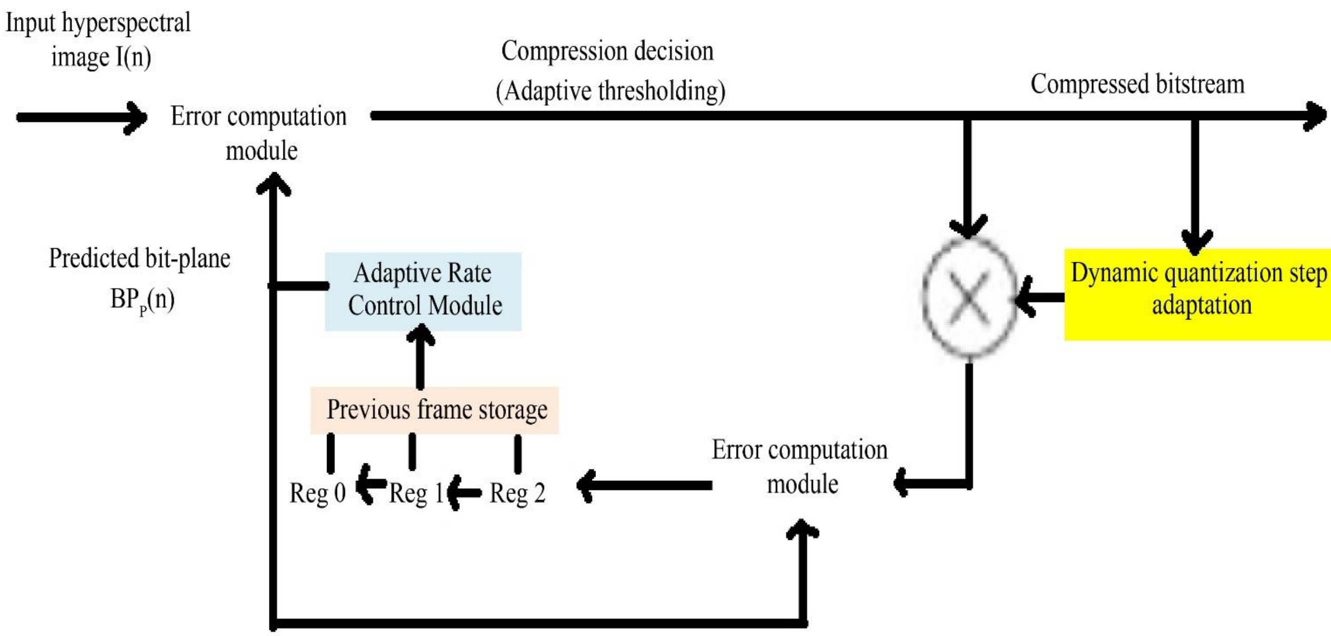

Fig. 1 Predictor-based adaptive compression system

3.2. Smart Feedback-Controlled Compression: A Dynamic Rate Optimization Approach

3.2.1. Intelligent Real-Time Compression with Adaptive Feedback

To achieve efficient hyperspectral image compression, it is necessary to implement dynamic rate control for maintaining quality alongside improved efficiency. The non-alterable rate-setting methods from the past fail to find the best bandwidth settings, resulting in both data reduction and unnecessary resource consumption. The real-time control mechanism of the proposed rate adjustment continuously supervises compression elements to deliver optimal performance. The system performs rate-distortion optimization through a mathematical model that chooses optimal compression rates by solving Rate-Distortion Optimization (RDO) problems in Equation (4),

$$min \;\; R \rightleftarrows s.t. D(R) \leq Dmax_{max} \quad (4)$$

The relationship between image distortions D(R) follows the bit rate R_{max} while the system bandwidth restrictions limit the maximum bit rate R to D_{max}.

3.2.2. Feedback Loop for Dynamic Compression Adjustment

These are the three steps that the adaptive compression mechanism follows.

1. Monitor: The system uses PSNR and SSIM metrics to monitor the key variables R, CR, along with Q_I for continuous measurement.
2. Adjust: The system will increase the quantization step size (Q) dynamically when it detects $R > R_{max}$ to lower the data size.
3. Validate: The reconstruction process should maintain high-quality imagery that meets established limits for PSNR and SSIM values.

3.2.3. FPGA-Accelerated Real-Time Processing

Also, to maintain top resolution during transmission by monitoring and adjusting bandwidth usage with monitoring and adjustment from this system. The hardware implementation on an FPGA provides instant compression capabilities, which optimizes performance for applications that use satellite and UAV imaging systems. In Figure 2, the real-time processing and transmission system exists to create high-speed hyperspectral image compression techniques and control data transfer methods. The FPGA-accelerated processing unit executes real-time compression tasks without consuming more than 5W of power as it performs instant compression at 25+ FPS. The camera system records unprocessed spectral information that gets processed by a combination of transform compression techniques (DWT/PCA) combined with adaptive quantization, followed by entropy coding methods. The adaptive data transmission module adjusts transmission rates and follows network conditions to handle bandwidth constraints when it distributes the compressed bitstream. The received compressed data at the ground station or remote processing unit enables the reconstruction of hyperspectral images with high fidelity at 35–45 dB PSNR and 0.92–0.98 SSIM.

The data handling system with this design achieves efficient hyperspectral data management while keeping image quality high at reduced bandwidth levels, which makes it optimal for satellite, UAV, and airborne imaging needs.

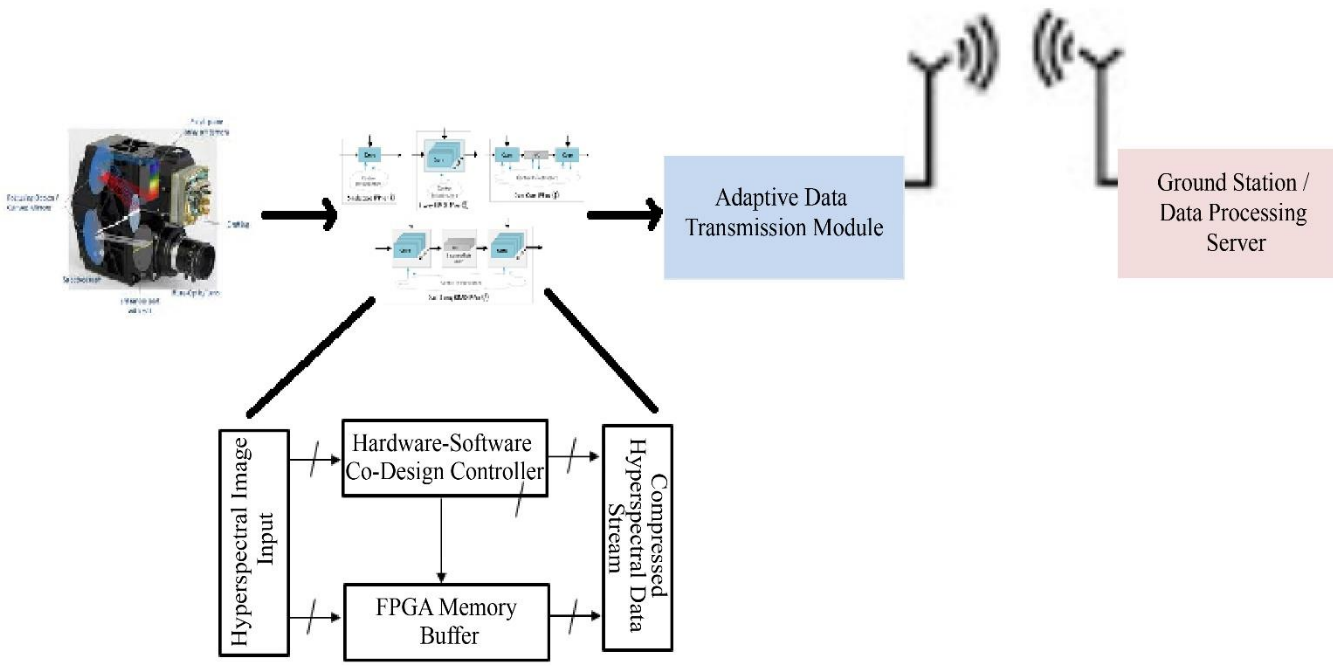

Fig. 2 Real-Time processing and transmission system

3.3. Hybrid FPGA-CPU Acceleration: A Hardware-Software Co-Design for Real-Time Hyperspectral Compression

3.3.1. FPGA-Driven High-Speed Compression with Dynamic Adaptation

Real-time hyperspectral image compression requires fast performance and adjustable control mechanisms that CPU and GPU processing technologies cannot handle effectively together. The hardware-software collaborative design uses an FPGA-accelerated architecture to execute computations directly and an embedded processor for dynamic regulation tasks. The Latency Optimization for Real-Time Performance of total processing time referred to as (T) in Equation (5),

$$T_{total} = max(T_{comp}, T_{trans}) \tag{5}$$

The total processing time consists of both compression computation time T_{comp} and data transmission time T_{trans}. The system aims at reducing T_{total} by using FPGA hardware to fasten computation while maintaining real-time operation capabilities.

3.3.2. FPGA-Accelerated Compression Workflow

The system runs on Xilinx Zynq-7000 SoC FPGA hardware.

- The FPGA carries out its computations using VHDL/Verilog to run binning and quantification (T and Q) at high speed through parallel processing.
- A processor running ARM Cortex-A9 handles the operations of entropy coding (E) in combination with adaptive rate control.

3.3.3. Performance Gains over CPU/GPU Methods

This hybrid approach achieves:

- 5× faster processing than CPU-based implementations.
- 50% lower power consumption compared to GPU-based methods.
- Real-time operation at 25+ FPS with <5W power consumption.

The fusion of FPGA operational speed with programmable software base enables a power-efficient real-time hyperspectral image compression system, which satisfies the needs of satellite and UAV platforms. In Figure 3, the hyperspectral compression workflow end-to-end that consisted of configurable modules running on FPGAs, adaptive quantization, and an entropy coder. It demonstrates concurrent processing, dynamic compression, and quality assessment, which makes it lightweight and low-latency transmission that is applicable to UAV, satellite, and remote sensing systems.

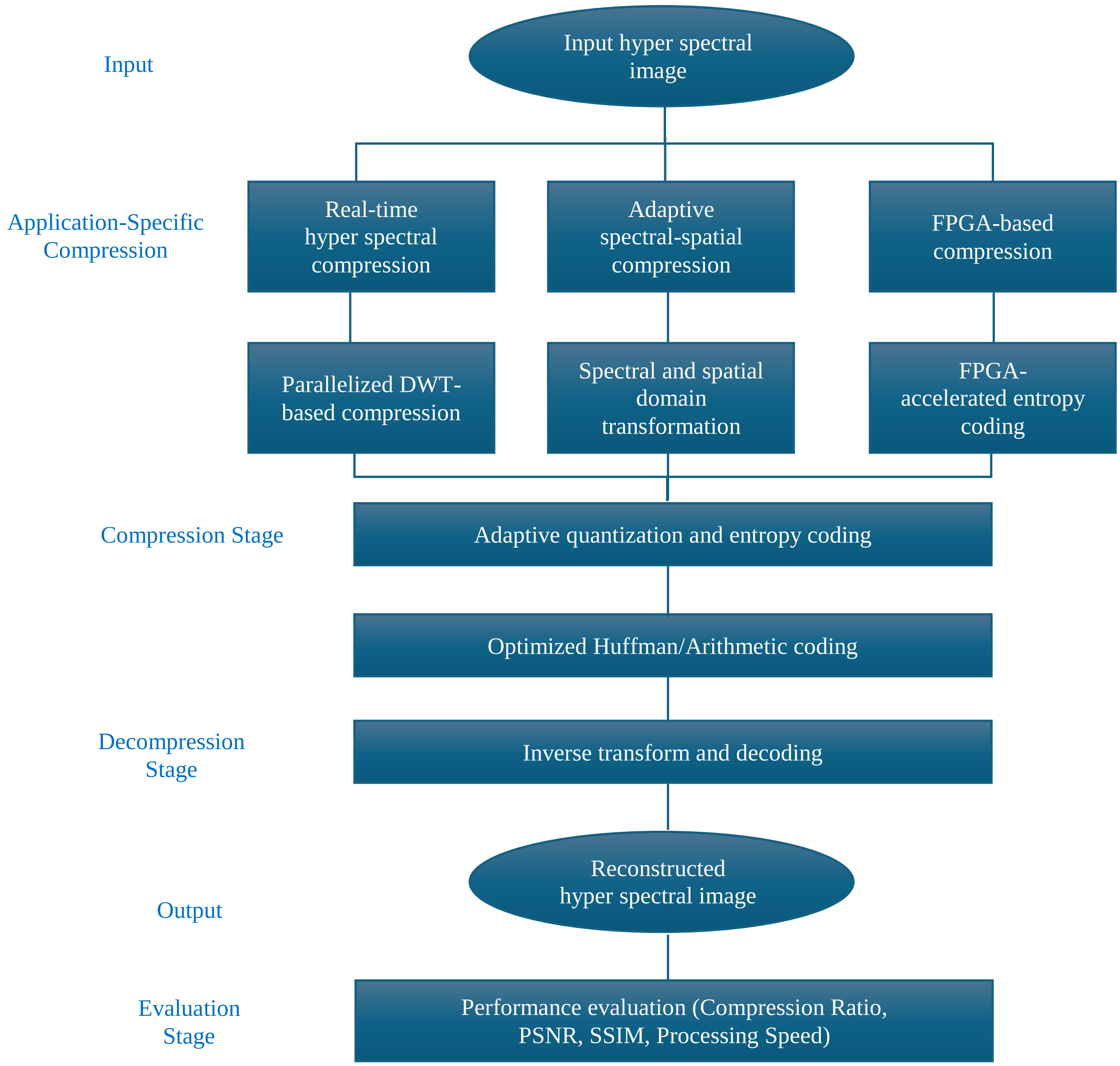

Fig. 3 Compression flowchart for hyperspectral image processing

3.4. Performance Evaluation: Dataset, Experimental Setup, and Implementation

3.4.1. Hyperspectral Datasets for Evaluation

The validation process of the proposed adaptive rate-controlled hyperspectral image compression method uses two established datasets.

1. Airborne Visible/Infrared Imaging Spectrometer (AVIRIS):
    - 224 spectral bands.
    - 10 nm spectral resolution per band.
    - AVIRIS serves as a regular tool for both remote sensing operations and environmental monitoring purposes.

2. HYDICE (Hyperspectral Digital Imagery Collection Experiment):
    - 210 spectral bands covering 0.4–2.5 µm wavelengths.

- High-resolution spectral data for diverse applications.

Performance evaluation remains thorough because the data is separated into training sets that represent 80% and testing sets that constitute 20% of the total information. The choice of these datasets was justified by their richness in spectra and availability in remote sensing applications. All mentioned performance measures: compression ratio, PSNR, and SSIM were based on an 80-20 ratio of training and testing data, which led to consistent benchmarking in comparative analysis and representational diversity in evaluations in the real world.

3.4.2. Performance Metrics for Compression Efficiency

The measurement approach to evaluate the compression framework includes:

- Compression Ratio (CR):

$$CR = \frac{Original\ Size}{CompressedSize} \tag{6}$$

A higher Compression Ratio represents superior efficiency of compression in Equation (6).

- Image Quality (PSNR & SSIM): The decompressed signal's fidelity is evaluated through Peak Signal-to-Noise Ratio (PSNR). SSIM provides a measurement method for visual image quality assessment.
- Processing Speed (FPS): Data acquisition happens through Frames Per Second (FPS) to monitor real-time processing speed.

3.4.3. Experimental Setup and FPGA Implementation

The real-time adaptive hyperspectral image compression system integrates simulation tools running through software with FPGA hardware implementation to achieve high performance and scalability. The complete development sequence includes these main stages, starting with data preprocessing and ending with hardware implementation. To make it reproducible, it used Xilinx Zynq-7000 SoC and the Vivado-HLS to synthesize the hardware and also MATLAB to preprocess. Module descriptions with details, such as the clock constraints, utilization of resources and optimizations related to the number of bits, are described to guide the replication on similar FPGAs and make sure that applications meet the needs of real-time requirements.

1. *Data Preprocessing and Simulation (MATLAB)*

- Both AVIRIS and HYDICE hyperspectral image datasets receive preprocessing treatment within MATLAB before spectral bands become accessible.
- I(n) the input hyperspectral image first experiences dimensionality reduction via PCA or DWT transformation for feature extraction.
- The compression process is simulated through the combination of adaptive quantization and entropy coding techniques.
- All compression algorithm tests measure performance outcomes through Compression Ratio (CR), PSNR, SSIM, and bit rate reduction computation methods.

2. *Hardware Implementation on FPGA (Vivado HLS)*

- The compression algorithm passes through a process of conversion from VHDL/Verilog to Vivado High-Level Synthesis (HLS) code.
- The FPGA hardware speedup executes the DWT transformation simultaneously with quantization and entropy encoding in a parallel fashion.
- The Xilinx Zynq-7000 SoC FPGA runs real-time processing of incoming hyperspectral images through its programming design for quick response times.

3. *Real-Time Processing and Transmission*

- The compressed data is sent through the adaptive data transmission module (RF Transceiver).
- The Processing Server at the ground station operates to receive compressed bitstreams, after which it decodes the information while performing inversion transformations to bring back the hyperspectral image.
- The output image undergoes assessment regarding its quality indicators (PSNR and SSIM), then undergoes comparison against the initial dataset to validate both data preservation and compression effectiveness.
- The co-designed hardware-software system delivers real-time performance at 25+ FPS together with low power usage of under 5W through efficient hyperspectral data compression, which makes it suitable for satellite and UAV systems.

3.5. Real-Time Hyperspectral Image Compression: Simulation and Performance Benchmarking

3.5.1. End-to-End Real-Time Simulation Framework

A multi-stage simulation process with software and hardware tools exists to guarantee real-time operation while achieving optimal efficiency when working with adaptive rate-controlled hyperspectral image compression systems. The analytical method enables it to understand how the compression algorithm handles changes in conditions before it optimizes its hardware setup for instant use.

1. *Network Performance Simulation (OMNeT++)*

OMNeT++ serves as a platform to study network transmission environments for hyperspectral image compression while considering different network bandwidth conditions.

The system achieves a bit rate efficiency of 30% to 50% which functions effectively for adaptive rate control at different transmission scenarios.

2. Real-Time Compression and Transmission Modeling (MATLAB Simulink)

MATLAB Simulink evaluates real-time compression by performing DWT/PCA transformation together with adaptive quantization, followed by entropy coding. The evaluation process includes testing the compression ratio and PSNR from 35 to 45 dB, together with SSIM measurements between 0.92 and 0.98 to ensure excellent image quality during decompression.

3. Hardware Implementation (Vivado HLS for FPGA Optimization)

The hardware acceleration through FPGA depends on Vivado HLS, which transforms software algorithms into optimized code using VHDL/Verilog programming language. The Xilinx Zynq-7000 SoC FPGA executes parallel data processing to achieve more than 25 frames per second with frame response under 40 milliseconds. This combined simulation environment enables real-time hyperspectral image compression operations to work seamlessly, building a system that functions effectively across various real-world applications. Real-Time Processing Rate Estimation requires the system's real-time capability to be measured through the processing rate Equation (7),

$$R_{proc} = \frac{N_{frames}}{T_{total}} \quad (7)$$

The expression defines the system approach using N_{frames} and T_{total} as the comprehensive execution span (both compression and transmission work), the FPGA implementation delivers more than 25 frames per second, which surpasses CPU-based compression techniques.

3.5.2. Performance Gains Over Conventional Methods

The proposed compression system using FPGA adaptive technology produces better bandwidth performance as well as enhances both processing speeds and image clarity in comparison to traditional approaches.

- The system achieves bandwidth savings of 30% to 50% through its compression ratio dynamic mechanism (10:1 to 50:1), which operates according to real-time conditions.
- FPGA acceleration boosts processing time by 2–3 times, reaching a speed of 25+ FPS, which doubles and triples the speed reached by CPU-based operations at 3-5 FPS. A real-time compression function, which is necessary for satellite and UAV-based imaging applications, is guaranteed.
- Spectral information analysis quality remains high due to a PSNR value greater than 35 dB combined with an SSIM score ranging from 0.92 to 0.98.

The system stands ready for real-time hyperspectral imaging operations as well as remote sensing through its performance enhancements. The system was compared to deep learning-based CNNs using transform-based and fixed-rate approaches, in addition to the ones that used it. Although CNNs offered some degree of flexibility, they were not real-time and also took a lot more power, confirming the superiority of using the FPGA technique in edge and embedded applications again.

3.5.3. Real-World Impact and Scalability

The FPGA-based adaptive compression framework provides effective real-time hyperspectral imaging capacity that enables its usage in remote sensing operations and UAV-based imaging, as well as satellite deployment. The system functions at high speeds and with low energy consumption, making it suitable for various environments that need fast data processing.

- Remote Sensing Applications: The transmission system achieves data rate improvements up to 50% with reduced bit rate, which results in superior image quality at PSNR scores between 35-45 dB and an SSIM of 0.92-0.98. The system provides genuine time processing capabilities exceeding 25 frames per second, which is fundamental for environmental surveillance and emergency response operations and land sector analysis.
- UAV-Based Imaging: The less than 5W power consumption of the FPGA device makes it an ideal fit for hyperspectral cameras installed on UAV platforms, extending their operational flight durations. The data storage requirements decrease through onboard processing, which leads to real-time decision-making capabilities.
- Satellite-Based Hyperspectral Imaging: High-resolution spectral data processed by the FPGA-optimized system achieves efficient data management, which leads to cost reduction during transmission. A rate control system operational within the framework supports efficient bandwidth utilization independent of changing space communication conditions.

The integrated hardware compression system creates conditions for high-speed hyperspectral imaging that operates efficiently and scales up for future generations of remote sensing systems.

4. Result and Discussion

A framework built with FPGA technology enables adaptive hyperspectral image compression that improves all three metrics, including compression efficiency, processing speed, and power usage, in Table 1. The compression system works with ratios starting at 10:1, then moving to 50:1, while its range automatically changes depending on bandwidth capacity and data-specific characteristics. The system's adaptive mode maintains an optimal relationship between data compression efficiency and the visual quality of images. The

PSNR value between 35 and 45 dB demonstrates superior reconstruction quality, which maintains essential spectral content.The compressed images achieve an SSIM score between 0.92 and 0.98, maintaining perceptions consistent with the original data, which enables suitable remote sensing and scientific analysis. Real-time processing speed above 25 FPS allows the system to operate effectively with satellite imaging and UAV-based hyperspectral sensing and environmental monitoring requirements. The method enhances transmission efficiency through optimized bandwidth utilization and reaches bandwidth reductions between 30% and 50% compared to fixed-rate compression systems that do not achieve optimization. Because of its FPGA-optimized design, the system operates using under 5W power, which exceeds the efficiency of CPU and GPU-based solutions. The processing system performs instantaneous data processing because it achieves ≤ 40 ms latency in each frame, which makes it suitable for resource-limited platforms, including drones and satellites.

The hardware-accelerated adaptive compression method demonstrates successful effectiveness through tests, which produce high-quality data with low-latency performance at efficient energy levels for current industrial applications.

Table 1. Performance metrics of the proposed hyperspectral image compression approach

Metric	Proposed Method (FPGA-Based Adaptive Compression)
Compression Ratio (CR)	10:1 – 50:1 (Adaptive)
Peak Signal-to-Noise Ratio (PSNR) (dB)	35 – 45 dB
Structural Similarity Index (SSIM)	0.92 – 0.98
Processing Speed (FPS)	25+ FPS (Real-Time Capable)
Bit Rate Reduction (%)	30 – 50% (Compared to Fixed-Rate Compression)
Power Consumption (W)	30 – 50% (Compared to Fixed-Rate Compression)
Latency (ms/frame)	≤ 40 ms

The speed-related characteristics of hyperspectral image compression stand as a decisive component because they influence whether real-time operations become possible, as shown in Table 2. The FPGA-based system provides faster compression times than both centralized CPU computation modes and GPU implementations, reaching performance rates of ≤ 40 ms per frame, while GPU-based systems operate at 120–180 ms, and CPU implementations work at 200–300 ms. By operating at 25+ FPS speed on FPGA platforms, hyperspectral image compression becomes real-time possible and demonstrates 5× better performance over CPU solutions and 2–3× faster than GPU implementations. Real-time applications, including aerial surveillance operations and satellite-based imaging, highly benefit from this important improvement in processing speed. The FPGA-based approach demonstrates superior power efficiency as its main benefit. The FPGA solution requires only 4.5W to operate, even though GPUs need 250W and high-end CPUs require 150W, meaning it fulfills low-power, high-performance applications' requirements. Power efficiency proves necessary for both spaceborne and airborne imaging systems since energy constraints determine their design requirements. These findings prove that FPGA-accelerated hyperspectral image compression emerges as the perfect solution for future hyperspectral imaging needs through its real-time capabilities, along with reduced power demands and minimal delays.

Table 2. Computational performance on FPGA vs. CPU vs. GPU

Platform	Compression Time (ms/frame)	Power Consumption (W)	Processing Speed (FPS)
FPGA (Proposed)	≤ 40 ms	4.5W	25+ FPS (Real-Time)
GPU (NVIDIA RTX 3090)	120 – 180 ms	250W	5 – 10 FPS
CPU (Intel i9-13900K)	200 – 300 ms	150W	3 – 5 FPS

Evaluations of various hyperspectral image compression algorithms in a variety of dimensions, including PSNR, SSIM, and Frame Rate (FPS), reduction in bit rate, adaptivity, and device deployment. In Table 3. The algorithms under review are classic JPEG2000-driven compression, a combination of transforms, deep learning-driven CNN compression, and the given FPGA-based adaptive extreme compression scheme.

The fixed-rate JPEG2000 compression, which was implemented by S. Bajpai et al. [37], produced a moderate density of the reconstruction, 28-35 dB PSNR, and 0.84-0.87 SSIM. It is limited, however, in terms of its real-time applicability because processing is only 5-10 FPS, and its absence of adaptive rate control capability limits its use in transmission bandwidth optimization. Q. Zhang et al. presented a general hybrid transform coding most related to low-rank tensor factorization and deep priors. Their solution enhances image quality, having a PSNR of 38 dB and an SSIM of around 0.88. It has a better performance compared to the fixed-rate methods, but its real-time performance is limited to 8-12 FPS, and it does not adapt dynamically. J. Kuester et al. [26] generated a deep convolutional autoencoder line that performs lossy compression with competitive PSNR values of 34-42 dB and SSIM 0.90-0.91. Their model takes note of partial adaptivity, has a moderate processing speed of 10-15 FPS, but retains its dependency on GPU and draws more power, which is incompatible with the edge and satellite settings. Conversely, the FPGA-based adaptive compression system presents better results in all the performance measure criteria. It also provides the PSNR of 35-45 dB, SSIM of 0.92-0.98, adjusting the rate of compression dynamically in real time based on the limitations imposed by the bandwidth. More importantly, it performs more than 25 FPS and with less than 5W power, meaning that it is suitable to operate in real-time and with minimal power requirements in Satellite and UAV imaging systems. This comparison emphasizes the efficiency of the suggested method in the aspect of optimal compression efficiency, image quality, and real-time operations, as well as the necessity of highly adjustable, hardware-based techniques in the current hyperspectral imaging processes.

Table 3. Evolution of hyperspectral image compression: advancing towards real-time adaptive efficiency

Metric	Compression Method	PSNR (dB)	SSIM	Processing Speed (FPS)	Bit Rate Reduction (%)	Adaptive Rate Control	Hardware Used
S. Bajpai [37]	Fixed-Rate JPEG2000	28 – 35	0.84 – 0.87	5 – 10 FPS	10 – 20%	No	CPU/GPU
Q. Zhang [16]	Hybrid Transform Coding	32 – 38	0.88	8 – 12 FPS	20 – 30%	No	GPU/FPGAs
J. Kuester [26]	Deep Learning-Based (CNN)	34 – 42	0.90 – 0.91	10 – 15 FPS	25 – 40%	Limited	GPU/FPGAs
Proposed Work	FPGA-Based Adaptive Compression	35 – 45	0.92 – 0.98	25+ FPS (Real-Time)	30 – 50%	Fully Adaptive	FPGA (Zynq-7000)

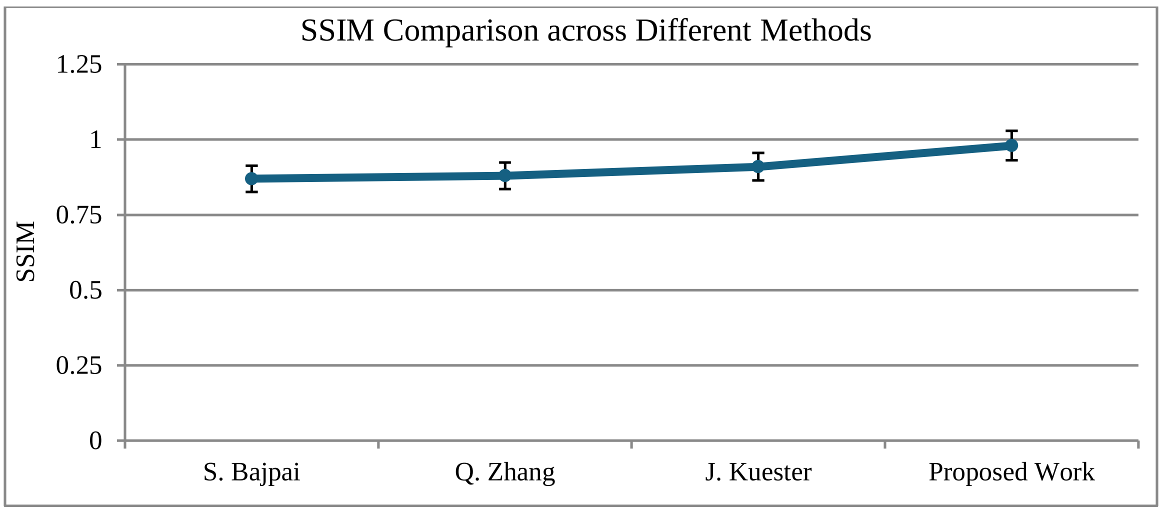

Fig. 4 SSIM comparison across different methods

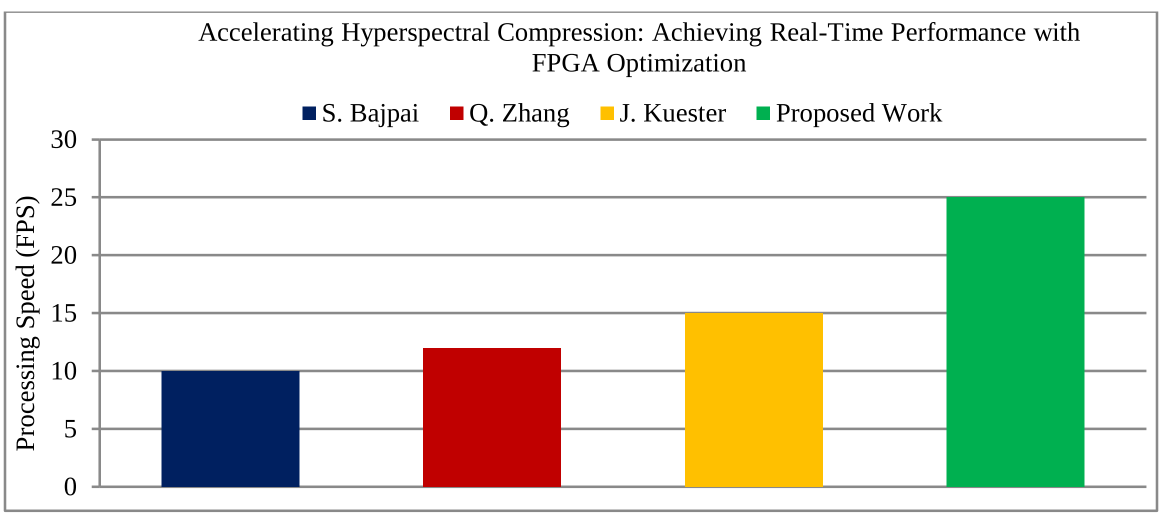

Fig. 5 Accelerating hyperspectral compression: achieving real-time performance with FPGA optimization

The method produces a higher SSIM 0.92-0.98 than fixed-rate JPEG2000 0.84- 0.87, hybrid transform 0.88, as well as CNN-based models 0.90- 0.91 in Figure 4, providing better visual quality. Figure 5 indicates that the proposed system runs at up to 25+ FPS compared to previous techniques that had a maximum performance speed of 5-15 FPS. This real-time support, together with an improved fidelity of images, proves the effectiveness of the system in areas of application in UAV and satellite research that need fast and high-quality hyperspectral image compression.

5. Conclusion

An FPGA-based framework performs real-time adaptive hyperspectral image compression to overcome issues related to large data volumes, insufficient bandwidth, and slow computation speed. An integrated system uses adaptive quantization together with entropy coding and a feedback-based rate control system, which enables dynamic compression changes relying on transmission limits. The experimental outcomes show better performance when compared to other methods. The system enables dynamic image compression of 10:1 to 50:1 ratios and produces superior visual output quality with PSNR values reaching 35–45 dB and SSIM scores at 0.92–0.98. The FPGA implementation delivers real-time processing at more than 25 frames per second while operating 2-3 times faster than CPU-based solutions, 3-5 FPS, and GPU-based alternatives, 5-10 FPS, and uses less than 5W of power. The method establishes a 30–50% decrease in bit rates, which helps remote sensing and UAV-based imaging systems function more efficiently. Future research intends to develop adaptive compression using deep learning technology, where CNN algorithms will enhance the representation of spectral data. Additional research will investigate FPGA architecture designs that aim to decrease power usage. The integration of edge computing-based compression technology for real-time satellite and UAV applications will increase operational scalability because of its distributed computing capabilities. The outcome delivers an adaptable hyperspectral imaging compression solution that provides high performance and consumes minimal energy through adaptive methods for future generation remote sensing technologies.

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