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Modern Approaches to Lossless Compression: Entropy Coding, Transform Methods, and Deep Learning Models

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ABSTRACT

Digital data from multimedia systems, cloud computing, Internet of Things (IoT), medical imaging, remote sensing, and AI has grown exponentially, creating a need for effective data storage and transmission. Lossless compression plays an important part in minimizing storage requirements and communication bandwidth, and in providing a perfect reconstruction of the original data. Lossless compression does not discard any data, and is essential for certain applications, where data integrity and accuracy is paramount, including medical diagnostics, scientific computing, legal documentation, and hyperspectral imaging. In this paper, a detailed literature survey on the latest developments of the lossless compression technologies 2018-2026 is presented. Classical entropy based methods, predictive coding models, transform based compression, and new neural-network assisted compression frameworks are covered. Special focus is paid on medical image compression, hyperspectral image coding, audio compression, and compression of foundation models. Context dependent prediction, entropy-aware transformations, integer wavelet transforms and deep learning based universal compressors are critically examined and compared. In addition, the study underscores the increasing importance of artificial intelligence for improving the compression performance using adaptive learning and intelligent redundancy reduction techniques. Comparative evaluations show that the present machine learning based and neural network based methods can lead to better compression efficiency and still maintain the lossless reconstruction capability. Lastly, current challenges, emerging trends and future research directions are discussed, such as the application of edge computing, efficient compression strategies for large-scale foundation models and next-generation systems, and compression enabled by AI.

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1. INTRODUCTION

Digital technologies, cloud computing, Internet of Things (IoT) devices, multimedia applications and scientific simulations and artificial intelligence have created an unprecedented surge in data production at world level. Many of the image, audio, video, medical, hyperspectral and sensor data are too large to be stored, transmitted and processed efficiently. Data compression is thus an essential part of today's computing systems that can lead to reduced storage space and communication bandwidth, while ensuring that the data is accessible and remains consistent. There are normally two types of compression techniques, which are lossy and lossless compression techniques, where information is discarded or not discarded in the process of compression [1, 2].

Lossless compression techniques are especially relevant in scenarios where it is essential to perfectly reproduce the original data. Lossless compression methods retain all data without discarding any information, and ensure that there is no loss of data when decompressing.Lossless algorithms do not throw away information to compress more, but preserve all information and guarantee perfect recovery after decompression. These properties make lossless compression essential for medical imaging, remote sensing, scientific data archives, legal documentation, financial systems, military systems, software archives and other applications where the integrity of the data is important [1], [2]. Thus, researchers have been continuously working to develop more sophisticated lossless compression algorithms, with the aim of increasing the compression efficiency with minimum computational complexity.

The classical lossless compression techniques involve mainly three techniques: reduction of statistical redundancies via entropy coding, dictionary based coding, and predictive coding, and transform based technique. Many modern compression standards have been based on the classical methods like Run-Length Encoding (RLE), Huffman Coding, Arithmetic Coding, Lempel-Ziv (LZ) based methods and Prediction by Partial Matching (PPM) [1]. The Huffman coding and arithmetic coding are still widely used entropy coding methods due to their capability of giving short coding for frequently occurring symbols. In the same way, there are many popular compression schemes like ZIP, PNG, and GZIP which have made use of dictionary-based algorithms like LZ77, LZ78 and LZW that are simple and efficient [2].

With the increasing demand for efficient image compression, there has been a significant amount of research on the advanced lossless image coding method. This has led to the research of higher compression performance based on context-based prediction models, reversible transformations, adaptive entropy coding and hybrid compression frameworks. Ungureanu, Negirla and Korodi [10] pointed out that region-of-interest preservation is a new challenge in image compression research and adaptive coding strategies that can adapt the compression structure to meet specific efficiency requirements without compromising image quality are the current focus of research. Likewise, transform techniques that take entropy into account have been shown to have good efficiency in reducing data redundancy prior to entropy encoding and thus to provide better compression ratios than traditional techniques [4].

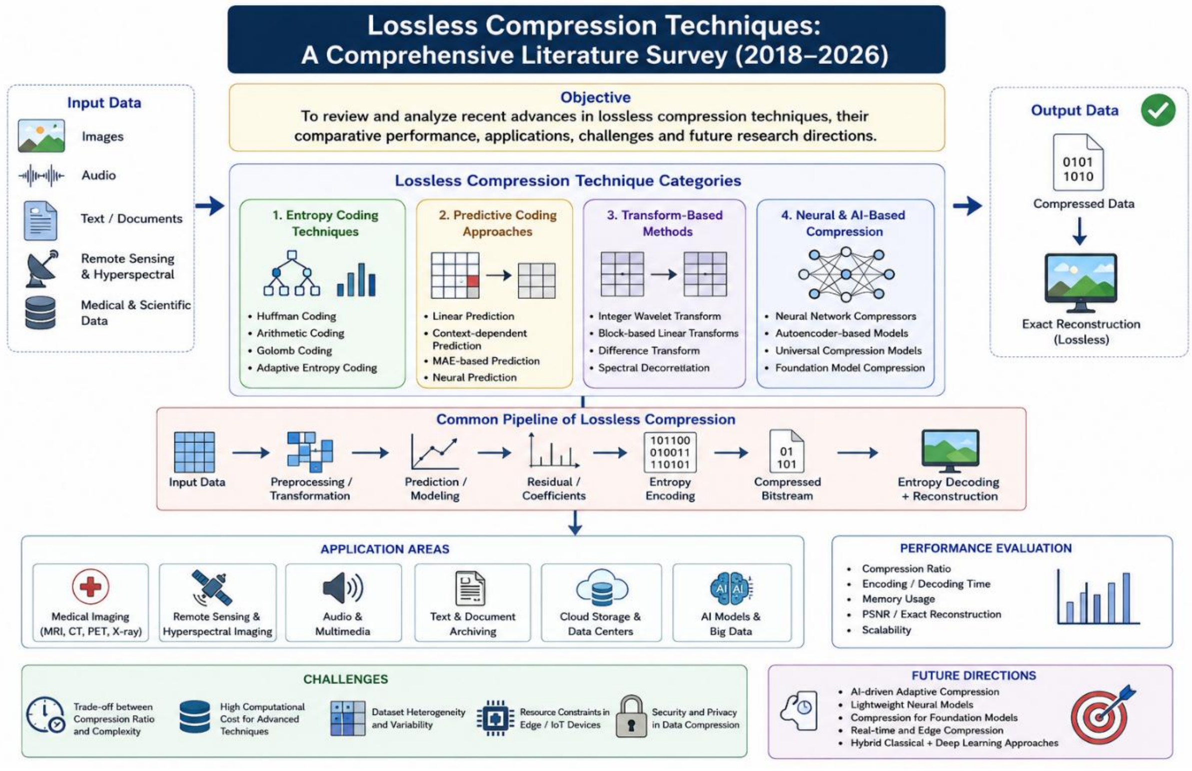

Fig. 1. Lossless compression techniques and usage

Medical imaging is one of the most important applications for lossless compression. Diagnostic images are created in enormous quantities in modern health care systems, obtained by means of magnetic resonance imaging (MRI), computed tomography (CT), positron emission tomography (PET) and ultrasound imaging. Lossless compression is sometimes preferred over lossy compression because it will maintain the fidelity of the image, important to maintain diagnostic accuracy. Xin and Fan [11] presented a new lossless compression technique for multi-component medical images based on big data mining techniques to enhance the compression performance without compromising the diagnostic information. Similarly, Rojas-Hernández et al. [14] proposed a difference-transform-based compression method for medical images and applied it to clinical images, achieving a good preservation of clinically relevant information while minimizing storage space.

Another important area of application is remote sensing and hyperspectral imaging, in which lossless compression is of crucial importance. This requires huge data, generated by hundreds of spectral bands from hyperspectral sensors, which have huge storage and transmission issues. Data integrity is crucial for remote sensing data that are used for environmental monitoring, agriculture, defense, and scientific analysis. Several studies have been conducted recently on hyperspectral image compression methods such as spectral decorrelation, predictive coding, and transform-based methods to enhance the compression performance. Altamimi and Ben Youssef [3] gave an extensive survey of the lossless and near-lossless hyperspectral image compression algorithms and highlighted the need for maintaining the spectral information. Likewise, Nagendran et al. [6] introduced a lossless hyperspectral compression scheme which uses spectral decorrelation and transform coding to achieve efficient reduction in the spectral-band-to-spectral-band redundancy.

There have been significant developments in recent years in predictive compression techniques. Context-dependent prediction methods predict future data by using the value of the nearby data points and only encode the residual errors, which reduces the value of the entropy and hence helps to achieve better compression. Context-dependent linear prediction model based on mean absolute error minimization was proposed by Ulacha and Łazoryszczak [5] and was shown to be more efficient in compression than the conventional predictors. Rajput et al. [15] further extended the predictive compression by introducing content-awareness mechanisms which dynamically adapt the prediction model depending on the image characteristics, which are suitable for efficient data sharing in distributed storage environments.

With the advent of machine learning and deep learning technologies, next-generation lossless compression systems have been significantly impacted. Unlike hand-designed predictors and coding schemes, complex statistical dependencies can be learned directly from data by a neural-network-based compression model. A duplex neural network architecture was proposed by Rhee et al. [12] that predicts both the values of the pixels and contextual information for lossless image compression, which outperforms the traditional methods. Recently, Sun et al. [7, 17] made a comprehensive survey and benchmark evaluation of the universal compressors based on neural networks, pointing out that the deep-learning-based models have become more and more effective for compression of multi-source data. These methods are fundamentally different from traditional statistical compression techniques and represent an exciting transition from statistics to intelligent data compression.

With image and multimedia compression, new research is now underway on compressing artificial intelligence models. Large foundation models have billions of parameters and are large to store and transmit. Hershcovitch et al. [8] and [18] explored lossless and near-lossless compression techniques for foundation models and showed that they can achieve significant compression of the model without sacrificing performance. These advancements suggest that compression will continue to play a significant role in not just data management, but also in the ability to efficiently deploy modern AI systems.

Though there has been tremendous progress, there are still challenges in the area of lossless compression. These involve balancing compression ratio with computation complexity, considering real-time data processing needs, optimizing algorithms for various data types and fitting intelligent learning mechanisms without heavy resource demands. This has led to an active continued research on entropy-aware transformations, adaptive prediction models, neural compression architectures, and domain-specific optimization strategies. The aim of this literature survey is to overview the recent progress of the lossless compression methods in the last 8 years (2018-2026), and to identify the main achievements, application areas, performance comparison, and future research trends in this fast-changing field.

2. LITERATURE REVIEW

Lossless compression is still a field of research because of the need to efficiently store and transmit large-scale digital data. In the recent years, the attention is given towards the enhancement in compression ratio, computational complexity reduction, and the application of the compression algorithms in specific areas like medical imaging, remote sensing, multimedia systems, artificial intelligence, etc. Although traditional entropy-based schemes remain the backbone of contemporary compression systems, recent research has aimed at developing new and improved predictive models, transform approaches, and neural-network based frameworks for better performance. This section summarizes the key insights into lossless compression research for 2018-2025.

2.1 Classical Lossless Compression and Entropy Coding Techniques

One of the simplest elements of a lossless compression system is entropy coding. Hussain et al. [1] did a detailed survey on image compression techniques and emphasized the importance of using entropy coding algorithms like Huffman coding and Arithmetic coding to reduce the redundancy in images. Their research showed that entropy coding is still an essential part of not only traditional compression systems, but also modern compression systems.

In the same way, Rahman and Hamada [2] gave a state of the art review of lossless image compression techniques and discussed the pros and cons of the classical techniques such as Run-Length Encoding (RLE), Huffman coding, Arithmetic coding, Lempel-Ziv-Welch (LZW), and Prediction by Partial Matching (PPM). The authors found that while these methods are reliable and produce good compression of data, the efficiency of compression is sometimes limited by the statistical nature of the data.

Sharma and Batra [9] have considered different compression algorithms in terms of information security and storage efficiency. According to their results, entropy-based algorithms remain good in terms of compression ratio and computational complexity, and therefore, are applicable to a variety of practical applications.

The classical compression methods have been tried to be enhanced in recent years by using adaptive coding and entropy optimization. The improvements are designed to be better utilised by exploiting the characteristics of the data, while keeping the simplicity and reliability of the traditional compression frameworks.

Table 1. Comparison of Classical Lossless Compression Studies

Ref.	Technique	Application Domain	Key Findings
[1]	Entropy Coding Survey	Image Compression	Comprehensive review of lossless techniques
[2]	Classical Compression Survey	Images	Analysis of Huffman, Arithmetic, LZW, PPM
[9]	Compression Algorithm Analysis	Information Security	Performance comparison of compression methods
[13]	Arithmetic Coding + IWT	Image Compression	Improved coding efficiency

2.2 Prediction-Based and Transform-Based Lossless Compression

Prediction based compression techniques remove redundancy by predicting the value of the data from the previous samples and only encoding the prediction error. These methods have been shown to significantly improve compression for image and multimedia databases.

In a context-dependent linear prediction model, the authors Ulacha and Łazoryszczak [5] proposed a linear prediction model that minimizes the Mean Absolute Error (MAE). Their approach is a dynamic adaptation of prediction coefficients based on the local characteristics of the image and entails a substantial reduction in residual entropy. Experimental results demonstrated improved results than that of the traditional predictive coding methods.

There has also been a lot of research interest towards the transform based compression. Žalik et al. [4] presented a block-based linear transform framework for lossless image compression, which is entropy-aware. The proposed method successfully reduced the image entropy by using the reversible transformations before entropy coding, and increased the compression ratios.

Based on the Integer Wavelet Transform (IWT) and Arithmetic Coding (AC) schemes, Rahman et al. [13] proposed an image lossless compression scheme. They used the decorrelation properties of wavelet transforms without losing the image's perfect reconstruction property. The results showed significant improvements in the compression efficiency compared to the traditional compression methods without using a transformer.

Content-aware predictive compression mechanism was proposed by Rajput et al. [15] for high throughput network storage environments. The structure can dynamically adapt the prediction parameters according to the content of the image, which improves the compression quality of the image and decreases the transmission overhead.

Table 2. Comparison of Prediction and Transform-Based Compression Techniques

Ref.	Year	Method	Compression Strategy	Main Contribution
[4]	2024	Entropy-Aware Transform	Reversible Transform Coding	Reduced image entropy
[5]	2024	Context-Dependent Prediction	MAE-Based Prediction	Improved compression ratio
[13]	2022	Integer Wavelet Transform	Wavelet + Arithmetic Coding	Better decorrelation
[15]	2022	Content-Aware Prediction	Adaptive Predictive Coding	Efficient data sharing

2.3 Lossless Compression for Medical and Hyperspectral Images

Medical imaging and remote sensing applications present very large data sets that must be stored and transmitted efficiently and retain information integrity. Thus, lossless compression is heavily researched in these areas.

In order to solve the above-mentioned problems, Xin and Fan [11] introduced a lossless compression model for multi-component medical images using big-data mining techniques. Their technique was effective in detecting redundancies between channels of images and provide better compression without impairing the diagnostic value of the image.

Likewise, Rojas-Hernández et al. [14] proposed a lossless compression technique for medical images using difference transformation method. The proposed technique minimized redundancy by encoding the differences between the transformed image, leading to efficient storage without compromising image fidelity.

With the advent of modern remote sensing systems, which now collect large amounts of data in the spectral domain, hyperspectral image compression has become an important application field. Altamimi and Ben Youssef [3] discussed recent developments of lossless and near-lossless hyperspectral image compression algorithms. Their survey pointed out that more and more predictive coding, transform coding, and spectral decorrelation methods were now being used to preserve spectral information.

Nagendran et al. [6] put forward one lossless hyperspectral image compression method based on spectral decorrelation and transform coding. Experimental results showed that a considerable amount of data redundancy was reduced in the various spectral bands without loss of the original hyperspectral images.

Table 3. Comparison of Domain-Specific Lossless Compression Methods

Ref.	Domain	Method	Key Advantage
[11]	Medical Imaging	Big Data Mining Compression	Multi-component redundancy reduction
[14]	Medical Imaging	Difference Transform	Diagnostic quality preservation
[3]	Hyperspectral Imaging	Survey of HSI Compression	Comprehensive review
[6]	Hyperspectral Imaging	Spectral Decorrelation + Transform Coding	Improved spectral compression

2.4 Neural Network-Based and Emerging Compression Techniques

With the advent of the new generation of artificial intelligence, a new wave of compression algorithms has emerged that leverage machine and deep learning models. Such techniques automatically discover complex statistical relationships from data and are usually superior to hand-made compression methods.

A duplex neural network architecture was proposed for lossless image compression by Rhee et al. [12] Jointly predicting both the pixel value and contextual information using a framework allows the estimate of the probability to be more accurate and lowers the cost of entropy coding. Their findings showed that they performed better than the traditional predictive coding approaches.

A thorough survey and benchmark evaluation of the universal compressors based on neural network were carried out by Sun et al. [7], [17]. They took an in-depth look at several deep learning architectures and emphasized the use of neural compressors for multi-source data. According to the authors, neural compression systems can be very effective at capturing complex patterns that are not easily exploited using traditional statistical methods.

Another new frontier is the compression of AI models. Large foundation models need to be deployed with large storage resources and communication bandwidth. Hershcovitch et al. [8] and [18] explored lossless and near-lossless compression methods for foundation models, respectively, and showed substantial model size reduction without compromising predictive performance. This research is one of the latest trends towards smart compression frameworks for AI systems.

Moreover, Mineo and Shouno [16] investigated optimization methods for lossless audio coding based on natural-gradient methods of learning. They found that convergence rates and coding efficiency can be improved in audio applications by using a machine-learning-assisted optimization.

Table 4. Comparison of AI-Based Lossless Compression Techniques

Ref.	Year	Technique	Application	Major Contribution
[12]	2021	Duplex Neural Network	Image Compression	Joint pixel-context prediction
[16]	2022	Natural Gradient Optimization	Audio Compression	Improved convergence rate
[7], [17]	2025	Neural Universal Compressors	Multi-Source Data	Benchmark evaluation
[8], [18]	2024	Foundation Model Compression	AI Models	Storage reduction for large models

The literature survey reveals a progressive transition from the classical entropy-based compression methods to intelligent, adaptive, and application-specific compression framework with lossless compression. The traditional techniques like Huffman coding, arithmetic coding and predictive coding are still the basic techniques of compression [1], [2] and the recent ones include medical image compression [11], [14], hyperspectral image coding [3], [6] and deep learning based universal compression models [7], [12], [17] which focus on context-aware prediction, reversible transforms and etc. Recent studies in foundation-model compression [8, 18] further emphasize the growing importance of compression for next-generation AI systems, which is essentially lossless. All the above developments suggest that the future of compression should be more and more machine learning-based, adaptive prediction, and domain-specific optimization to obtain better compression performance and wider applicability.

3. CONCLUSION

In today's digital landscape, lossless compression remains a vital part of data storage and transmission, especially in scenarios where data integrity and accuracy are paramount, such as broadcasting. Today, lossless compression is still significant in many data storage and communication applications, particularly in video broadcasting, where it is essential to maintain perfect data integrity and exact reconstruction. The surveyed research focused on recent advances for the lossless compression techniques of classical entropy based methods, predictive coding methods, transform based methods and emerging neural network based compression methods during the period of 2018-2026. Although many newer methods exist, the traditional methods of Huffman coding, arithmetic coding, dictionary-based coding, and predictive compression are still used as a building blocks in many practical compression systems, because of their reliability and computational efficiency. In recent years, however, it has been shown that the use of more powerful data-specific redundancies through the use of context-aware prediction models, entropy-aware transforms and adaptive coding strategies can significantly improve the compression performance. In addition, there is a growing number of applications where domain-specific compression solutions are taking importance, such as medical imaging, hyperspectral remote sensing, audio processing and processing of large-scale scientific datasets. Moreover, the application of AI and deep learning in compression frameworks has brought novel possibilities to build AI and adaptive lossless compressors that can learn complex data distributions. Despite the data growth and diversification, neural-network-based universal compressors and compression methods for foundation models are promising avenues to solve the problems. Researchers are likely to explore further advances in AI-supported compression architectures, light-weight compression for edge and IoT devices, federated and privacy-preserving compression architectures, and efficient compression methods for large language models and foundation models. Moreover, hybrid approaches using classical entropy coding techniques in conjunction with deep learning prediction methods can provide better compression rates without compromising on computational efficiency. Scalable, adaptive and intelligent lossless compression techniques will continue to be an important research focus to support next-generation storage, communication, and artificial intelligence applications as data continues its downward trend of exponential growth.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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