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MODERN FILE COMPRESSION METHODS

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Анотація

У статті розглянуто сучасні методи стиснення файлів, зокрема методи без втрат і з втратами. Розглянуто їх застосування, переваги та останні досягнення у сфері стиснення на основі штучного інтелекту.

Ключові слова: стиснення файлів, стиснення без втрат, стиснення з втратами, кодування Хаффмана, LZW, DEFLATE, Brotli, Zstd, JPEG, MP3, AAC, H.264, H.265, стиснення на основі штучного інтелекту.

Abstract

The article discusses modern file compression methods, including lossless and lossy techniques. It explores their applications, advantages, and the latest advancements in AI-based compression.

Keywords: file compression, lossless compression, lossy compression, Huffman coding, LZW, DEFLATE, Brotli, Zstd, JPEG, MP3, AAC, H.264, H.265, AI-based compression.

Introduction

File compression is an essential technology in the digital world, allowing for a reduction in file sizes to improve storage efficiency and data transmission speed. With the increasing demand for data storage and transfer, modern compression methods continue to evolve, balancing efficiency, speed, and lossless or lossy data retention. Various contemporary file compression methods and their applications have been examined.

Lossless compression methods

Lossless compression techniques allow for the exact reconstruction of the original file after decompression. These methods are widely used for text, software, and some types of image and audio compression. They rely on efficient encoding schemes to remove redundancy without sacrificing any information.

Huffman coding is a lossless data compression algorithm that assigns variable-length codes to input characters based on their frequency. The most frequently occurring symbols are assigned shorter codes, while less frequent symbols get longer codes. This results in efficient storage without losing any original data. Huffman coding is used in various file formats, including JPEG and MP3, for efficient entropy encoding [1].

One of the advantages of Huffman coding is its ability to achieve optimal compression rates when dealing with non-uniform data distributions. However, prior knowledge of the frequency distribution is required, which can be a limitation in dynamic applications where real-time compression is needed.

Lempel-Ziv-Welch (LZW) is a dictionary-based compression algorithm widely used in image formats such as GIF and some implementations of TIFF. Unlike Huffman coding, LZW replaces repeated sequences of characters with shorter dictionary-based codes, reducing redundancy in the data. As the algorithm processes a file, it builds a dictionary of previously encountered sequences, allowing efficient encoding and decoding [2].

The primary benefit of LZW is its ability to compress text and image data effectively without any loss of information. However, the compression ratio depends heavily on the input data. Files with many repeated patterns benefit greatly, while highly random data may see little improvement.

Deflate (DEFLATE) is a widely used compression algorithm that combines LZ77 and Huffman coding to achieve high compression ratios. This method is the foundation for file formats such as ZIP, GZIP, and PNG. LZ77 identifies repeated substrings and replaces them with references, while Huffman coding further optimizes the encoding process [3].

One of the strengths of DEFLATE is its balance between compression efficiency and speed. It is particularly effective in scenarios where quick decompression is required, such as web content delivery and software distribution.

Brotli is an advanced compression algorithm developed by Google that builds upon DEFLATE while introducing modern optimizations. It uses a combination of dictionary-based compression and Huffman coding, enabling higher compression ratios compared to traditional methods like GZIP [4].

Brotli is widely used in web applications due to its ability to deliver smaller file sizes while maintaining fast decompression speeds. Many modern browsers and web servers support Brotli for efficient web page loading, reducing bandwidth consumption and improving user experience.

Zstandard (Zstd) was created by Facebook as a high-performance compression algorithm designed for both high compression ratios and fast decompression. Unlike traditional methods, Zstd employs entropy coding and advanced dictionary techniques to achieve efficient compression with minimal computational overhead [5].

Zstd is particularly useful in cloud storage, big data applications, and network transmission where speed and efficiency are crucial. It allows users to adjust compression levels dynamically, making it suitable for various performance-sensitive scenarios.

Lossy compression methods

Lossy compression methods achieve higher compression ratios by discarding some data, which can result in a loss of quality. These methods are common for multimedia files, where some loss is acceptable. The main goal of lossy compression is to remove information that is less perceptible to human senses while maintaining acceptable quality.

JPEG is a widely used image compression format that utilizes discrete cosine transform (DCT) to reduce image file sizes while maintaining acceptable visual quality. The algorithm divides images into small blocks and applies DCT to remove high-frequency details that the human eye is less sensitive to.

The major advantage of JPEG is its ability to significantly reduce file sizes, making it ideal for digital photography and web images. However, aggressive compression settings can introduce noticeable artifacts, reducing image quality [6].

MP3 (MPEG Audio Layer 3) is a widely recognized audio compression format that uses perceptual coding to remove inaudible frequencies from audio recordings. By eliminating sounds that the human ear cannot perceive, MP3 achieves substantial file size reductions without a noticeable loss in quality for most listeners.

The MP3 format has been instrumental in digital music distribution, allowing for efficient storage and streaming. However, lower bitrates can lead to degraded sound quality, particularly in complex audio compositions [7].

AAC (Advanced Audio Codec) is an advanced audio compression format that provides better sound quality than MP3 at similar bitrates. It employs improved psychoacoustic models and frequency masking techniques to achieve higher efficiency in data reduction [8].

AAC is commonly used in streaming services, mobile devices, and online media platforms. It supports multiple audio channels and provides high-quality audio experiences even at low bitrates.

H.264 and H.265 (HEVC) are video compression standards that achieve high compression by analyzing both spatial and temporal redundancies in video frames. H.264 (AVC) was widely adopted for HD video, while H.265 (HEVC) offers even greater efficiency by reducing bitrate requirements for the same visual quality [9].

These formats are essential for video streaming, broadcasting, and storage. H.265, in particular, has become the standard for 4K and 8K video content due to its superior compression capabilities.

Hybrid and AI-based compression

Modern advancements in artificial intelligence and hybrid algorithms are reshaping compression techniques. These new approaches leverage machine learning and statistical models to optimize compression efficiency beyond traditional methods.

Neural compression methods leverage deep learning models to optimize compression efficiency. By training neural networks to understand patterns in data, these methods achieve superior compression ratios without compromising quality. Google's JPEG AI is an example of how neural networks can enhance traditional compression methods, resulting in better image preservation at lower file sizes [10].

Context-Based Adaptive Binary Arithmetic Coding (CABAC) is a sophisticated entropy coding technique used in video compression standards like H.264 and H.265. It dynamically adjusts encoding based on statistical models, leading to higher compression efficiency. While CABAC improves compression performance, it requires more computational resources, making it best suited for high-quality video applications [11].

Perceptual coding prioritizes perceptually significant data while discarding redundant or less noticeable information. It is widely used in audio and video compression to maximize quality retention within limited storage constraints. Perceptual coding has been a key factor in the development of efficient multimedia compression formats, ensuring that users experience minimal quality loss [12].

Applications of modern compression

Modern compression techniques play a crucial role in various industries. In cloud storage, compression is used to reduce storage costs and improve data retrieval speeds. Efficient compression methods enable large-scale storage of documents, images, and videos without excessive disk space consumption.

Streaming services rely on advanced compression algorithms to deliver high-quality video and audio while minimizing bandwidth usage. Platforms such as Netflix, YouTube, and Spotify use lossy and adaptive compression to optimize content delivery for different network conditions.

Big data applications benefit from compression to handle vast amounts of structured and unstructured data. Compressed databases and log files enable faster processing and lower storage costs, making data analytics and machine learning more efficient.

Conclusions

Modern file compression methods continue to evolve, integrating AI-driven techniques and advanced algorithms to meet the demands of data storage and transmission. The increasing reliance on cloud computing, multimedia streaming, and big data analytics further highlights the importance of efficient compression techniques. Future developments in AI-based compression and hybrid methods are expected to push efficiency even further, enabling better quality retention and faster processing speeds. Selecting the appropriate compression method remains crucial in balancing file size reduction, computational complexity, and quality preservation across different applications.

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