All\_Algorithms\_Performance\_Metrics

TABLE A1. Performance of Independent Compression Algorithms

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Algorithm** | **Data type** | **Compression Ratio** | **Compression Speed (MB/s)** | **Decompression Speed (MB/s** | **Efficiency** |
| **Pure lzma** | **Small File** | **3.60** | **35.26** | **281.19** | **0.4839** |
| **Pure lzma** | **Medium File** | **3.74** | **31.78** | **456.98** | **0.4010** |
| **Pure lzma** | **Large File** | **3.79** | **30.99** | **524.70** | **0.2438** |
| **Pure zstd** | **Small File** | **4.45** | **45.99** | **141.3** | **0.5406** |
| **Pure zstd** | **Medium File** | **4.59** | **76.61** | **389.41** | **0.6293** |
| **Pure zstd** | **Large File** | **94.49** | **546.22** | **593.79** | **0.6836** |
| **Pure Brotli** | **Small File** | **4.6** | **7.15** | **132.01** | **0.2847** |
| **Pure brotli** | **Medium File** | **5.00** | **38.38** | **259.61** | **0.437** |
| **Pure Brotli** | **Large File** | **117.11** | **312.66** | **426.47** | **0.6073** |
| **Pure bzip2** | **Small File** | **6.57** | **6.14** | **4.94** | **0.4236** |
| **Pure bzip2** | **Medium File** | **7.56** | **20.18** | **4.95** | **0.4717** |
| **Pure bzip2** | **Large File** | **9.77** | **18.75** | **4.88** | **0.021** |
| **Purelz4hc** | **Small File** | **3.60** | **28.24** | **142.08** | **0.3047** |
| **Purelz4h** | **Medium File** | **3.75** | **32.94** | **443.91** | **0.3986** |
| **Purelz4h** | **Large File** | **3.79** | **32.51** | **554.34** | **0.258** |

The performance analysis of independent compression algorithms shows that **Brotli and Zstd achieve the highest compression ratios**, particularly on large files, with Brotli reaching an anomalous **117.11x compression**—likely due to its **dictionary-based encoding and large window size**. **LZMA** provides a strong balance, offering **high compression ratios** with moderate speeds, while **Zstd excels in both compression and decompression speeds**, especially for large files. **LZ4HC** is the fastest for decompression but sacrifices compression efficiency. **Bzip2**, despite its high compression ratio, suffers from **extremely slow decompression speeds**, making it less practical for real-time applications. Overall, Zstd and Brotli stand out as the most efficient choices depending on whether **speed (Zstd) or ratio (Brotli) is prioritized**.

TABLE A2. Performance Analysis of Hybrid Compression Algorithms with LZMA Encoding

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Hybrid algorithm** | **Data type** | **Compression**  **Ratio** | **Compression Speed (MB/s** | **Decompression Speed (MB/s** | **Efficiency** |
| LZMA +zstd | **Small File** | 5.43 | 2.72 | 56.56 | 0.2952 |
| LZMA + zstd | **Medium File** | 6.51 | 2.85 | 125.85 | 0.3673 |
| LZMA + zstd | **Large File** | 139.79 | 6.03 | 383.77 | 0.567 |
| LZMA +Brotli | **Small File** | 5.44 | 3.45 | 83.51 | 0.3266 |
| LZMA +Brotli | **Medium File** | 6.51 | 2.46 | 120.12 | 0.3622 |
| LZMA +Brotli | **Large File** | 141.59 | 6.09 | 367.82 | 0.565 |
| LZMA +bzip2 | **Small File** | 5.34 | 3.43 | 56.94 | 0.2879 |
| LZMA + bzip2 | **Medium File** | 6.47 | 2.72 | 75.42 | 0.331 |
| LZMA + bzip2 | **Large File** | 139.77 | 5.82 | 349.25 | 0.552 |
| LZMA +lz4hc | **Small File** | 5.43 | 3.64 | 89.37 | 0.3324 |
| LZMA +lz4hc | **Medium File** | 6.51 | 2.71 | 121.80 | 0.364 |
| LZMA +lz4hc | **Large File** | 141.10 | 6.01 | 376.25 | 0.5678 |

For small files, all LZMA-based hybrids deliver similar compression ratios (≈5.4×) with modest compression speeds, while LZMA+lz4hc offers the highest decompression speed (≈89 MB/s). For medium files, ratios consistently reach about 6.5×, though LZMA+zstd provides the fastest decompression (≈126 MB/s) compared to the other combinations. In the large file category, both LZMA+Brotli and LZMA+lz4hc achieve excellent ratios above 139×, with LZMA+Brotli slightly higher (141.59×) while their compression and decompression speeds remain competitive.

TABLE A3. Performance Analysis of Hybrid Compression Algorithms with Zstd Encoding

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Hybrid algorithm | **Data type** | **Compression ratio** | **Compression Speed (MB/s)** | **Decompression**  **Speed (MB/s)** | Efficiency |
| Zstd + LZMA | **Small File** | 4.44 | 13.79 | 114.95 | 0.2928 |
| Zstd + LZMA | **Medium File** | 4.59 | 21.10 | 343.99 | 0.376 |
| Zstd + LZMA | **Large File** | 94.89 | 382.25 | 627.83 | 0.6539 |
| Zstd + brotli | **Small File** | 4.45 | 35.77 | 167.57 | 0.4951 |
| Zstd + brotli | **Medium File** | 4.59 | 70.34 | 354.94 | 0.582 |
| Zstd + brotli | **Large File** | 94.49 | 1071.57 | 537.24 | 0.8057 |
| Zstd + bzip2 | **Small File** | 4.39 | 25.89 | 87.68 | 0.3441 |
| Zstd + bzip2 | **Medium File** | 4.56 | 34.48 | 91.58 | 0.269 |
| Zstd + bzip2 | **Large File** | 94.30 | 623.42 | 534.89 | 0.6779 |
| Zstd + lz4hc | **Small File** | 4.45 | 46.31 | 283.02 | 0.6764 |
| Zstd + lz4hc | **Medium File** | 4.59 | 60.79 | 393.64 | 0.5678 |
| Zstd + lz4hc | **Large File** | 94.82 | 1055.69 | 663.78 | 0.8597 |

Hybrid compression using Zstd encoding shows a clear distinction in performance between small/medium and large files. For small and medium files, all combinations deliver compression ratios in the narrow range of approximately 4.4x to 4.6x, indicating that the redundancy in these datasets is reduced similarly regardless of the hybrid pairing. However, for large files, the compression ratios jump significantly to around 94x, demonstrating that these algorithms are especially effective at eliminating redundancy in extensive datasets. In terms of speed, Zstd combined with Brotli offers the fastest compression speed on large files (1071.57 MB/s), while Zstd + LZMA provides competitive decompression speeds (627.83 MB/s). Notably, Zstd + LZ4HC stands out with a balanced performance, achieving one of the highest decompression speeds (663.78 MB/s) while maintaining similar compression ratios and speeds as the other combination. While all hybrid combinations perform similarly on small and medium files, for large files, Zstd-based hybrids dramatically improve compression ratios. Among these, Zstd + LZ4HC offers the best overall performance with superior decompression speed, making it a highly efficient choice for applications dealing with large datasets.

TABLE A4. Performance Analysis of Hybrid Compression Algorithms with Brotli Encoding

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Hybrid algorithm | **Data type** | **Compression ratio** | **Compression Speed (MB/s)** | **Decompression Speed (MB/s)** | **Efficiency** |
| Brotli + LZMA | **Smallterm data** | 4.59 | 8.33 | 113.69 | 0.2742 |
| Brotli + LZMA | **Medium** | 5.00 | 12.15 | 287.89 | 0.348 |
| Brotli + LZMA | **large term data** | 117.5 | 208.44 | 431.69 | 0.5814 |
| Brotli + Zstd | **Smallterm data** | 4.60 | 30.56 | 235.89 | 0.543 |
| Brotli + Zstd | **Medium term data** | 5.00 | 36.70 | 311.11 | 0.462 |
| Brotli + Zstd | **large term data** | 117.10 | 491.50 | 450.03 | 0.6683 |
| Brotli + Bzip2 | **Smallterm data** | 4.53 | 17.99 | 66.09 | 0.2879 |
| Brotli + Bzip2 | **Medium term data** | 4.97 | 23.47 | 88.16 | 0.266 |
| Brotli + Bzip2 | **large term data** | 116.21 | 343.58 | 338.98 | 0.573 |
| Brotli + lz4hc | **Smallterm data** | 4.60 | 28.79 | 134.21 | 0.4357 |
| Brotli + lz4hc | **Medium term data** | 5.00 | 33.03 | 281.41 | 0.4283 |
| Brotli + lz4hc | **large term data** | 117.08 | 426.05 | 365.97 | 0.6116 |

The analysis of hybrid compression algorithms with Brotli encoding shows that for small and medium files, all combinations yield similar compression ratios (around 4.5x–5.0x). However, for large files, the compression ratios jump significantly—with Brotli + LZMA reaching 117.5x, Brotli + Zstd 117.10x, and Brotli + LZ4HC 117.08x, while Brotli + Bzip2 trails slightly at 116.21x. In terms of compression speed, Brotli + Zstd stands out for large files at 491.50 MB/s, considerably faster than Brotli + LZMA (208.44 MB/s), Brotli + Bzip2 (343.58 MB/s), and Brotli + LZ4HC (426.05 MB/s). Decompression speeds also favor Brotli + LZMA (431.69 MB/s) and Brotli + Zstd (450.03 MB/s) over the other methods. For large files, hybrid algorithms that combine Brotli with either LZMA, Zstd, or LZ4HC deliver outstanding compression efficiency, with Brotli + Zstd offering the fastest compression speed and Brotli + LZMA achieving the highest compression ratio.

TABLE A5. Performance Analysis of Hybrid Compression Algorithms with LZ4HC Encoding

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Hybrid algorithm | **Data type** | **Compression ratio** | **Compression Speed (MB/s)** | **Decompression Speed (MB/s** | Efficiency |
| LZ4HC+ LZMA | Small File | 4.12 | 11.28 | 63.53 | 0.1840 |
| LZ4HC +LZMA | Medium File | 4.26 | 12.79 | 79.29 | 0.1427 |
| LZ4HC +LZMA | Large File | 84.33 | 23.05 | 323.52 | 0.3838 |
| LZ4HC + Zstd | Small File | 4.09 | 32.47 | 323.83 | 0.5708 |
| LZ4HC + Zstd | Medium File | 4.24 | 34.49 | 485.04 | 0.482 |
| LZ4HC + Zstd | Large File | 67.40 | 35.18 | 553.80 | 0.4428 |
| LZ4HC + Bzip2 | Small File | 3.92 | 19.37 | 65.30 | 0.2145 |
| LZ4HC + Bzip2 | Medium File | 4.16 | 20.30 | 78.84 | 0.1624 |
| LZ4HC + Bzip2 | Large File | 13.55 | 21.52 | 107.54 | 0.0794 |
| LZ4HC + Brotli | Small File | 4.1 | 24.4 | 196.05 | 0.3964 |
| LZ4HC + Brotli | Medium File | 4.24 | 31.38 | 290.752 | 0.348 |
| LZ4HC + Brotli | Large File | 84.03 | 33.52 | 521.60 | 0.476 |

For small files, hybrid combinations using LZ4HC yield compression ratios in the narrow range of about 4.1×, with LZ4HC+Zstd delivering the highest compression speed (32.47 MB/s) and excellent decompression performance (323.83 MB/s). In medium files, ratios are around 4.16×–4.26×; here, LZ4HC+Zstd again leads with a high compression speed of 34.49 MB/s and an impressive decompression speed of 485.04 MB/s. For large files, the differences become more pronounced: LZ4HC+LZMA and LZ4HC+Brotli both achieve compression ratios in the mid-80s (84.33× and 84.03× respectively), while LZ4HC+Zstd shows a lower ratio (67.40×) but compensates with the fastest compression (35.18 MB/s) and highest decompression speed (553.80 MB/s). In contrast, LZ4HC+Bzip2 delivers a significantly lower ratio (13.55×) and slower speeds.

TABLE A6. Performance Analysis of Hybrid Compression Algorithms with LZ4HC Encoding

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | | **Hybrid Algorithm** | **Data Type** | **Compression Ratio** | **Compression Speed** | **Decompression** | **Efficiency** | | Bzip2 + LZMA | Small File | 6.55 | 8.26 | 51.06 | **0.4788** | | Bzip2 + LZMA | Medium File | 7.55 | 10.59 | 47.39 | 0.4584 | | Bzip2 + LZMA | Large File | 9.80 | 13.30 | 48.63 |  | | Bzip2 + Zstd | Small File | 6.57 | 19.68 | 46.18 | 0.5556 | | Bzip2 + Zstd | Medium File | 7.55 | 19.26 | 43.17 | 0.4908 | | Bzip2 + Zstd | Large File | 9.76 | 18.97 | 49.97 | 0.0415 | | Bzip2 + Brotli | Small File | 6.57 | 17.47 | 53.96 | 0.5476 | | Bzip2 + Brotli | Medium File | 7.56 | 18.89 | 43.73 | 0.4907 | | Bzip2 + Brotli | Large File | 9.77 | 17.38 | 50.62 | 0.041 | | Bzip2 + LZ4HC | Small File | 6.56 | 19.55 | 52.37 | 0.5591 | | Bzip2 + LZ4HC | Medium File | 7.55 | 18.55 | 46.22 | 0.4899 | | Bzip2 + LZ4HC | Large File | 9.76 | 18.09 | 40.97 | 0.0372 | |  |  |

For small files, all Bzip2-based hybrids achieve a similar compression ratio (≈6.57×), but those combined with Zstd and LZ4HC compress much faster (≈19.6 MB/s) compared to Bzip2+LZMA (≈8.26 MB/s) and Bzip2+Brotli (≈17.47 MB/s), with decompression speeds being comparable. For medium files, the ratios are around 7.55×, yet Bzip2+LZMA again lags in speed (≈10.59 MB/s) while the others maintain speeds near 18–19 MB/s. In large files, although all methods reach high ratios (≈9.76×–9.80×), Bzip2+LZMA remains the slowest in compression (≈13.30 MB/s) compared to the other hybrids (≈17–19 MB/s). Overall, Bzip2+Zstd and Bzip2+LZ4HC offer the best balance between compression efficiency and speed across file sizes