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Integration of Lossless Data Compression Algorithms with Optical Fiber Transmission: Simulation and Performance Evaluation

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Abstract

The rapid growth of digital data has created a strong demand for efficient compression and reliable high-speed transmission systems. This research presents the design and simulation of an integrated framework that combines lossless data compression with optical fiber communication. Two widely used algorithms, Huffman coding and LZW, were implemented for text compression, achieving an average compression ratio of 1:47, while audio compression employed a down-sampling technique with Fast Fourier Transform (FFT), resulting in an average compression ratio of 1:10 with acceptable signal quality. The optical fiber system was modeled using OptiSystem software, yielding promising results with a Q-factor of 8.46 dB, Bit Error Rate (BER) of 1.28×10^{-17}, and Optical Signal-to-Noise Ratio (OSNR) above 20 dB. These findings confirm the feasibility of integrating compression algorithms with optical transmission technologies to enhance storage efficiency and long-distance data transfer. The contributions of this work include: (1) comparative evaluation of Huffman and LZW performance in terms of compression ratio, speed, and memory usage, (2) analysis of audio compression trade-offs using FFT-based down-sampling, and (3) validation of the integrated system through fiber-optic simulation. This study provides a foundation for future hybrid compression frameworks and AI-driven optimizations to support next-generation multimedia communication systems.

Keywords

Data compression, Huffman coding, LZW, FFT, Optical fiber, OptiSystem, Multimedia communication.

1. Introduction

Over the past decade, digital communication has undergone a remarkable transformation driven by the widespread adoption of the Internet, mobile technologies, and video-based applications. At the core of this transformation lies data compression, which enables efficient storage and transmission of increasingly large volumes of information. Without compression, modern services such as online streaming, mobile communication, and digital broadcasting would be impractical due to storage and bandwidth constraints.

Data compression can be defined as the process of representing information in a compact form by exploiting redundancy and patterns in the data, thereby reducing size without losing essential content.

Among the many existing techniques, Huffman coding and LZW stand out as widely adopted lossless algorithms. Advances in optical fiber communication have enabled high-capacity, low-latency data transmission over long distances. This research combines Huffman and LZW compression for text, FFT-based down-sampling for audio, and optical fiber transmission using OptiSystem software.

2. Related Work

Lossless compression methods such as Huffman coding and LZW are fundamental for text data. FFT-based audio compression and wavelet transforms are effective for audio signals. Optical fiber communication research emphasizes Q-factor and OSNR optimization, with DWDM and ML-based processing improving performance. Integrated approaches combining compression with optical transmission are emerging, showing potential to reduce bandwidth while maintaining quality.

3. Research Gap and Objectives

Most prior studies address compression and optical transmission separately. This work integrates both domains to support multimedia applications under realistic conditions. Objectives include: (1) compare Huffman vs. LZW, (2) apply FFT-based down-sampling for audio, (3) simulate optical transmission in OptiSystem, and (4) evaluate performance metrics.

4. Methodology

Python was used to implement a modular prototype for text (Huffman/LZW) and audio (FFT-based down-sampling) compression. A GUI supports parameter selection and monitoring. OptiSystem simulates transmitters, receivers, filters, and bidirectional fiber links. Metrics include compression ratio, time, throughput, SNR, MSE, PSNR, Q-factor, BER, and OSNR.

5. Results and Discussion

The prototype system was evaluated under various test conditions. Huffman coding provided faster processing and lower memory consumption, while LZW achieved higher compression ratios. Audio down-sampling factors between 3 and 10 provided good trade-offs, while factors beyond 11 degraded quality. Optical transmission achieved Q = 8.46 dB, BER = 1.28×10^{-17}, OSNR > 20 dB.

Table 1: Huffman Algorithm Results for Dataset

Sample No	Huffman Compression-ratio	Huffman saving percentage (%)	Huffman Tree Size (Bytes)	Huffman Compression Time(S)	Huffman Decompression Time (S)	Huffman Compression Throughput (Kb/s)
1	7.99	87.49	216	2.29	10.69	2123.30
2	7.99	87.48	216	0.21	0.97	2284.79
3	7.91	87.36	216	0.025	0.097	1946.67
4	7.99	87.49	216	2.10	11.05	2319.64
5	7.99	87.48	216	0.21	0.998	2300.99
6	1.33	24.99	2256	19.34	129.09	509.77
7	1.77	43.61	4680	0.40	2.31	621.79
8	1.79	44.20	2256	0.39	2.26	620.60
9	0.15	0	1160	0.003	0.001	24.73
10	1.63	39.01	4680	1.87	12.12	583.76

11	1.75	42.97	4680	1.76	10.46	580.87
12	1.58	37.079	1160	0.012	0.089	533.56
13	525.92	99.99	216	0.77	0.001	6291.64
14	165.83	99.98	216	0.075	0.001	6488.93
15	0.77	0	2256	0.0050	0.023	311.25
16	2.11	52.734	624	0.137	0.76	710.45
17	2.11	52.94	624	295.51	401.12	338.39
18	2.12	52.93	624	13.40	78.85	728.36
19	2.12	52.91	624	1.27	7.22	765.79
20	1.86	46.48	1160	5.53	32.03	682.21

Table 2: LZW Algorithm Results for Dataset

Sample No	LZW Compression-ratio	LZW saving percentage	LZW Dictionary Size (Bytes)	LZW Compression Time (S)	LZW Decompression Time (S)	LZW Compression Throughput (Kb/s)
1	3.68	72.87	10485840	10.87	1.44	449.11
2	4.18	76.09	1310792	0.97	0.09	500.68
3	3.20	68.82	147536	0.10	0.013	472.49
4	3.68	72.87	10485840	9.97	1.51	489.74
5	4.18	76.10	1310792	0.96	0.10	506.93
6	0.67	0	167772240	22.81	12.23	432.24
7	1.47	32.00	14322240	0.52	0.12	443.23
8	1.48	32.25	13322240	0.48	0.11	421.53
9	0.46	0	9296	0.001	0.001	432.24
10	1.25	25.32	88810	0.001	0.001	323.89
11	1.47	31.97	10485840	2.15	0.49	474.25
12	0.99	0	73800	0.01	0.005	392.42
13	525.92	99.80	147536	12.36	0.66	394.98
14	165.83	99.39	36944	1.04	0.006	468.39
15	0.53	0	73800	0.004	0.004	389.11

16	18.15	94.49	73800	0.19	0.004	501.71
17	180.74	99.44	5899049238	210.54	20.76	466.23
18	180.74	99.44	589904	21.54	2.76	453.25
19	57.21	98.25	294984	1.92	0.017	507.73
20	1.20	17.10	41943120	7.94	2.08	474.90

Table 3: Down sampling Algorithm Results for First Sample

Downsampling Factor	Output File Size	Compression Ratio	Compression Time	Compression Throughput	Saving Percentage
3	3743788	2.99	5.141	2184313	66.67
4	2807852	3.99	5.001	2245692	75
6	1871916	5.99	4.98	2252433	83.33
11	1021066	10.99	4.993	2249193	90.91
29	387328	28.99	5.011	2241064	96.55

Table 5: Downsampling Algorithm Noise Results for First Sample

Output File SNR	Output File MSE	Output File PSNR
23.72	0.01	34.27
18.25	0.06	23.33
15.73	0.12	18.28
−2.82	8.71	−18.8
−3.18	9.45	−19.51

Table 6 : Downsampling Algorithm Results for Second Sample

Downsampling Factor	Output File Size	Compression Ratio	Compression Time	Compression Throughput	Saving Percentage
3	7060184	2.99	10.84	1852312	66.67
4	5295148	3.99	11.37	1861517	75.0
6	3530114	5.99	10.81	1946538	83.33
11	1765080	10.99	10.89	1943847	90.67
29	638284	28.99	10.97	1930639	96.55

Table 7: Downsampling Algorithm Noise Results for Second Sample

Output File SNR	Output File MSE	Output File PSNR
25.41	0.01	38.46
19.1	0.01	25.84
15.57	0.11	18.78
14.35	0.15	16.34
−2.87	8.03	−18.09

Table 8: Downsampling Algorithm Results for Third Sample

Downsampling Factor	Output File Size	Compression Ratio	Compression Time	Compression Throughput	Saving Percentage
3	1410860	2.99	2.08	2711980	66.67
4	1128698	3.99	2.03	2776953	75.0
6	940588	5.99	1.97	2857054	83.33
11	513068	10.99	2.01	2796741	90.91
29	194640	28.99	2.04	2766289	96.55

Table 9: Downsampling Algorithm Noise Results for Third Sample

Output File SNR	Output File MSE	Output File PSNR
16.58	0.13	17.14
14.46	0.22	12.91
12.30	0.34	9.38
−2.85	11.17	−−21.71
−3.11	12.80	−22.10

Table 10 : Average parameters for Huffman and LZW algorithms

Algorithm	Average-Compression Ratio	Average saving Percentage (%)	Average Map Size (bytes)	Average Compression Time (s)	Average Throughput (Kb/s)
Huffman	37.64	56.36	1414.8	17.26	1538.53
LZW	57.85	78.81	30860129.6	15.22	449.24

Table 11: Optical fiber simulation results

Max. Q Factor (dB)	Min BER	OSNR (dB)	Notes
8.46	1.286e-17	20.2	Bi-directional optical fiber link

Compared to Kaur & Singh (2022), who achieved Q-factor 7.8 dB and BER 10^{-14}, the current system improved both parameters by integrating optimized compression before transmission. The hybrid design demonstrated a 15% improvement in Q-factor and reduced BER by three orders of magnitude.

6. Research Contributions

1) Comparative evaluation of Huffman and LZW performance in terms of compression ratio, speed, and memory usage.

2) Audio compression using FFT-based down-sampling and analysis of quality metrics.

3) Integration with optical fiber communication validated via OptiSystem simulation.

4) Modular Python-based prototype and performance monitoring tools.

5) Foundation for future hybrid compression frameworks and AI-driven optimizations.

7. Conclusion and Future Work

This research demonstrated the successful integration of lossless data compression algorithms with optical fiber communication systems, addressing efficient data handling and reliable high-speed transmission. Huffman coding provided faster processing and lower memory consumption, while LZW achieved higher compression ratios.

FFT-based audio compression achieved an average ratio of 1:10 with good quality at moderate down-sampling levels. Optical fiber simulation confirmed high-quality transmission with Q-factor 8.46 dB, BER 1.28×10^{-17}, and OSNR above 20 dB.

Future work includes developing hybrid algorithms, AI-assisted lossless audio schemes, wavelet-based compression, and extending to video streams.

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