Fixed Bit Coding

High-Speed, Lossless Data Compression for Small Data Sets

L. Stevan Leonard

January 1, 2021

# Introduction

Compressing small amounts of data is an application that most data compression algorithms cannot address efficiently. Some of these algorithms, including LZW methods, become viable with more than 32 data values. The fixed bit coding method described in this paper is designed to compress and decompress 2 to 64 bytes as quickly as possible. By determining compression ratios of selected data sets with Huffman coding, fixed bit coding is estimated overall to produce results that are close to Huffman coding, the optimal frequency-based algorithm. Benchmarking against QuickLZ shows the speed and compression tradeoff of using fixed bit coding implemented in a test bed that compresses an entire file.

The basic method employed by fixed bit coding is well known as using only the number of bits required to encode the number of unique characters in a data set. This algorithm performs this task as efficiently as possible, in part by ending the algorithm early if the predetermined number of unique values is exceeded, but primarily because the algorithm requires very little analysis. Fast execution speed, especially for decoding, results from encoding the same number of bits for every data value.

The fixed bit coding algorithm includes a text mode because English text is a common data format and a data type where small data sets cannot be compressed by fixed bit coding. The Alice in Wonderland text file alice29.txt from the Squash Compression Benchmark achieves 24.3% compression for 64 input values (see Table 8).

The algorithm also includes a single value mode where a single value repeats in at least 1/3 of the number of input values. In this case, any number of other unique values can occur while getting over 18% compression for 64 input values. This mode increases compression for the file mr by over 30% (see Single Value Data).

Although this paper does not address any specific application of fixed bit coding, its use for small data sets includes subsets of a data set where highly compressible bytes are known to exist. The high speed of scanning means that even when some sections of data cannot be compressed, the overhead for compressing smaller sets of data is very minimal and decode speed is extremely fast.

# Fixed Bit Coding Versus Other Compression Methods

Fixed bit coding is often used as the introduction of how Huffman coding increases data compression with a prefix code based on data frequencies. For small data sets, however, the overhead of storing the frequency of values plus the unique values dramatically reduces the resulting compression for Huffman coding. Huffman coding requires data analysis to determine the frequency of occurrence of data values, and its required CPU execution time removes it as a high-speed compression method. Arithmetic coding, or range encoding, is another method that achieves high data compression at the expense of CPU time, which also removes that method from consideration, although it can be applied to small data sets. And due to the limited amount of data in 64 bytes, a dictionary lookup method is not applicable, although some algorithms, such as QuickLZ, can sometimes compress data sets as small as 32 bytes.

Rather than using frequency of occurrence, fixed bit coding improves on speed of execution over Huffman coding by encoding repeated values without analysis of frequencies. This approach has the drawback of somewhat lower data compression, estimated to be about 10% overall, because the higher frequency values are not given fewer bits to encode them. Fixed bit coding achieves a good compression ratio by using a fixed number of bits to encode every input value. This results in extremely fast execution time for encoding and decoding. For highly compressible data, data with a lot of repeated values, fixed bit coding is initialized to generate at least 25% compression. Incompressible data is determined as early as possible so that the method runs as quickly as possible whether data is compressible or not.

# Overview of the Algorithm

Fixed bit coding operates on data sets of 2 to 64 bytes that contain from 1 to 16 unique values. After the number of unique values in the data is found to be within the range of that number of input values, every value in the input is encoded with a 1- to 4- bit value that represents which of the unique values occurs at that position in the data. To be effective, the encoding must compress enough bits to offset the number of unique values. With these limits known ahead of time, decisions about compressibility can be made as early as possible (see Table 2).

Because the encoding uses the same number of bits for every input, the generation of output and the later decoding can be done extremely efficiently, which reduces runtime. Unique values are written to the output array when they are first read from the input, and the position of the corresponding unique value for each input value is stored.

The text mode algorithm represents the 16 most frequently occurring values in a 4-bit value and encodes other values in 8 bits. A control bit for each value specifies which of the two encodings applies to it. For text data, usually at least 75% of values are one of these frequently occurring values, so text data usually compresses at 25%.

The single value mode algorithm accumulates counts of repeated values and identifies a value when its repeat count reaches the minimum single value repeat count: . This mode achieves at least 18% compression for 64 values.

The simplicity of this compression method leads to encoding and decoding at speeds of more than 100 megabytes per second on a Mac with a 1 GHz Dual-Core Intel Core M processor. This method works only on data with many repeated values and is initialized to compress when the compression ratio is at least 25%, or slightly less for text and single value data. The implementation can be modified to achieve a lower or higher compression ratio, where possible.

# Implementation

Fixed bit coding is implemented in the files at <https://github.com/lsleonard/fixed-bit-coding>. The **fbc264** function compresses 2 to 64 values, and calls **fbc25** for two to five values. Call **fbc25** directly to avoid the call overhead. All functions are defined static and are included in the fbc.h header file.

The algorithm does not generate an encoding for uncompressed data. The decoder must be supplied the number of original values because this value is not stored in the compressed data. Otherwise, all data required to decode the original compressed data is contained in the encoded data described above.

## Fixed Bit Coding Test Bed

The execution of the fixed bit coding test bed requires an input file name, and optionally the block size (number of character values to compress with default of 64) and loop count (with default of 1). The specified file of up to 20 Mbytes is read into memory. An array of unsigned long values is allocated to store whether data was compressed or not. Output files are named based on the input file. This array and the block size are written to a file appended with fbc.cq. The compressed or original data is written to a file appended with .fbc. The compressed percentage is printed, then compressed blocks, based on the bits returned by blocks that did compress, and compression time and rate. The decompress routine **fbc264d** or **fbc25d** is called after reading in the .fbc.cq and .fbc data files. Decompression rate and time is printed.

When the macro GEN\_STATS is defined in main.c, additional information about the data is printed, including number of uncompressed blocks and the percentage of encoded blocks by number of unique values.

As this algorithm is intended as a low-level tool for compression of small data sets, the implementation of how to manage compressed and uncompressed data is left for the application developer. For example, compressed data could be concatenated to save unused bits in the last byte of output. Also, the number of input values is not stored in the compressed data. The test bed does not attempt to compress the bits that represent whether compression occurred or not, although this data could be highly compressed in some cases. The results from running the test bed are similar to what you can expect in a memory-based usage of the function, although the overhead of maintaining the file structure increases execution time as the number of input values decreases.

## Special Handling of 2 to 5 Values

Handling of 2 to 5 values is done in the functions **fbc25** and **fbc25d** to allow direct calls for these very small data sets. In addition to supporting output of one or two bytes for one unique value (all values the same), 2 and 3 values support compression when two nibbles define the bytes, and 4 or 5 values support 2 unique values.

## Encoding Bits Generated by the Fixed Bit Algorithm

The encoding bits generated by the fixed bit algorithm are listed in Table 1. The text mode algorithm Is discussed separately.

Table : Bits Generated by Fixed Bit Coding

|  |  |
| --- | --- |
| Encoding Element | Bits Generated |
| Indicator bits for 1 to 4 encoding bits (based on number of unique values) | 1 bit=5, 2 bits=6, 3 bits=5, 4 bits=8  First bit: 1 for only one unique else 0  Next 4 bits: number of unique values minus 1  0 indicates text mode  Next 3 bits: output values or padding bits |
| Input values | (number of values - 1) \* number of encoding bits |
| Unique values | number of unique values \* 8 |

Using the elements in Table 1, the computation of bits required to compress the input values for number unique vales of 2 to 16 is:

The first input value always matches the first unique value, so only this value is not encoded.

The encoding for a single unique value is indicated by setting the low bit of the first byte to 1 and copying the low-order 6 bits of the value to the upper 6 bits. If the value has 00 in the upper bits, the second bit of the first byte is set to 1. Otherwise, that second bit is set to 0 and the upper two bits of the value are copied into the low-order two bits of the second byte. The compression ratio achieved varies from 37% for 2 values to 96% for 64 values, when two bytes are used to encode the repeated value. When one byte is used to encode a single value with 00 in the upper bits, compression ranges from 50% for 2 values to 98% for 64 values.

## Encoding Bits Generated by the Text Mode Algorithm

Text mode is indicated when the number of unique values in the first byte of the output is 0 and the next higher bit is also 0. Text mode is used based on the count of the number of the 16 most frequently occurring text chars in Table 2.

Table : Most Frequently Occurring Text Chars Plus Space Character

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| space | e | t | a | i | n | o | s | h | r | d | l | u | c | m | f |

To limit overhead in text mode, only 5/16 of the input values are scanned to count text mode characters. If the minimum count is not reached, fixed bit execution begins. If the count across all data values indicates text data, the text mode algorithm is used to encode data. Otherwise, fixed bit execution begins. The number of unique values is used to decide whether to use text mode or fixed bit coding. One control bit is generated for each input value to indicate a 4-bit text char or an 8-bit value. To simplify encoding and speed processing, control bits are grouped together in bytes that follows the first byte. Text chars are grouped two per 8-bit value.

## Encoding Bits Generated by the Single Value Mode Algorithm

Single value mode is indicated when the number of unique values in the first byte of the output is 0 and the next higher bit is 1. One control bit is generated for each input value to indicate the single repeated value or an 8-bit value. To simplify encoding and speed processing, control bits are grouped together in bytes that follows the first byte. These are followed by the single repeat value, then the 8-bit values.

## Determining Number of Unique Values and Minimum Input Values

At the core of fixed bit coding is the matching of number of unique values to minimum number of input values. As the number of unique values in a data set increases, the compression ratio decreases because there are fewer repeated values that can be replaced by a shorter code. Table 2 lists the minimum input values for each number of unique values, the corresponding bits generated using the algorithm, and the corresponding compression savings with a target of 25%. As more input values occur for a given number of unique values, the resulting compression savings increase. The table used by the algorithm can be modified to achieve higher or lower compression ratios, where possible, by adjusting the minimum number of input values required for a given number of unique values.

Table : FBC Minimum Input Values for Number of Unique Values to Achieve 25% Compression

|  |  |  |  |
| --- | --- | --- | --- |
| Number of Unique Values | Minimum Number of Input Values | Bits Generated | Data Compression Savings (Percent) |
| 1 | 2 | 8, 10 | 50, 37 |
| 2 | 4 | 24 | 25 |
| 3 | 7 | 42 | 25 |
| 4 | 9 | 54 | 25 |
| 5 | 14 | 84 | 25 |
| 6 | 17 | 101 | 25 |
| 7 | 20 | 118 | 26 |
| 8 | 22 | 132 | 25 |
| 9 | 38 | 228 | 25 |
| 10 | 42 | 252 | 25 |
| 11 | 46 | 276 | 25 |
| 12 | 50 | 300 | 25 |
| 13 | 54 | 324 | 25 |
| 14 | 58 | 348 | 25 |
| 15 | 62 | 372 | 25 |
| 16 | 64 | 388 | 24 |

# Comparison of Huffman and Fixed Bit Coding Methods

The following tables show compression ratio comparisons for Huffman and fixed bit coding methods with 64 input values. Table 4 shows the worst case for fixed bit coding, a single unique value repeating, while Table 5 shows the best case, all unique values repeating. Alternatively, these tables show the best and worst cases for Huffman coding. Table 6 shows an intermediate case where half the unique values repeat. Lastly, Huffman coding of English text is examined.

The bits compared are the count of bits generated to encode every value by each method plus, for Huffman header, the frequency of each unique that is required to build the binary tree for decoding. For both methods, the number of indicator bits is assumed to be 5 bits as described above. The frequency of unique values for 64 input values can be listed from most frequent to least as the order of occurrence of unique values is not needed for decoding. This means the bits required for the next value will be at most what is required for the current value, so they can be determined dynamically.

Table 4 shows the worst-case compression for fixed bit versus Huffman coding when only 1 of the unique values repeats. The Huffman header will always be 6 bits for this case. Fixed bit coding produces 20% less compression than Huffman coding across 2 to 16 unique values.

Table : Worst Case Compression for Fixed Bit Coding versus Huffman: 1 Unique Value Repeats, 64 Input Values

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Unique Values | Huffman  Bits | Header Bits | FBC Bits | Huffman (Percent) | FBC (Percent) | FBC vs Huffman (Percent) |
| 2 | 64 | 6 | 63 | 82.2 | 83.6 | 1.4 |
| 3 | 66 | 6 | 126 | 80.3 | 69.7 | -10.5 |
| 4 | 69 | 6 | 126 | 78.1 | 68.2 | -10.0 |
| 5 | 72 | 6 | 189 | 76.0 | 54.3 | -21.7 |
| 6 | 76 | 6 | 189 | 73.6 | 52.7 | -20.9 |
| 7 | 80 | 6 | 189 | 71.3 | 51.2 | -20.1 |
| 8 | 84 | 6 | 189 | 68.9 | 49.6 | -19.3 |
| 9 | 88 | 6 | 252 | 66.6 | 35.7 | -30.9 |
| 11 | 98 | 6 | 252 | 61.5 | 32.6 | -28.9 |
| 13 | 108 | 6 | 252 | 56.4 | 29.5 | -27.0 |
| 15 | 118 | 6 | 252 | 51.4 | 26.4 | -25.0 |
| 16 | 123 | 6 | 252 | 48.8 | 24.8 | -24.0 |

Table 5 shows the best-case compression of fixed bit versus Huffman coding where all unique values repeat equally. The Huffman header requires 6 bits for the first value, and for the next value no more than the bits to encode the previous value or the remaining values. Also, the final unique value’s repeat can be imputed. In this case, Huffman coding exceeds fixed bit compression only when the number of unique values for the bits required is the smallest for that number of bits, such as for coding 3 unique values in 2 bits or 5 unique values in 3 bits. Fixed bit coding here produces 2.3% more compression than Huffman coding across 2 to 16 unique values.

Table : Best Case Compression for FBC vs Huffman: All Unique Values Repeat Equally, 64 Input Values

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Unique Values | Huffman  Bits | Header Bits | FBC Bits | Huffman (Percent) | FBC (Percent) | FBC vs Huffman (Percent) |
| 2 | 64 | 6 | 63 | 83.2 | 84.6 | 1.4 |
| 3 | 106 | 11 | 126 | 72.5 | 70.7 | -1.8 |
| 4 | 128 | 14 | 126 | 66.0 | 69.1 | 3.1 |
| 5 | 153 | 18 | 189 | 58.8 | 55.3 | -3.5 |
| 6 | 170 | 22 | 189 | 53.1 | 53.7 | 0.6 |
| 7 | 182 | 26 | 189 | 48.4 | 52.1 | 3.7 |
| 8 | 192 | 24 | 189 | 45.3 | 50.6 | 5.3 |
| 9 | 206 | 27 | 252 | 40.4 | 36.7 | -3.7 |
| 11 | 226 | 33 | 252 | 32.2 | 33.6 | 1.4 |
| 13 | 241 | 39 | 252 | 25.0 | 30.5 | 5.5 |
| 15 | 251 | 45 | 252 | 18.8 | 27.3 | 8.6 |
| 16 | 256 | 34 | 252 | 18.4 | 25.8 | 7.4 |

Table 6 shows that for 64 input values, when half the unique values repeat equally, FBC produces 4% less compression than Huffman coding, on average.

Table : FBC Versus Huffman with Half the Unique Values Repeating Equally, 64 Input Values

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Unique Values | Huffman  Bits | Header Bits | FBC Bits | Huffman (Percent) | FBC (Percent) | FBC vs Huffman (Percent) |
| 2 | 64 | 6 | 63 | 83.2 | 84.6 | 1.4 |
| 3 | 96 | 11 | 126 | 74.4 | 70.7 | -3.7 |
| 4 | 99 | 11 | 126 | 72.3 | 69.1 | -3.1 |
| 5 | 130 | 16 | 189 | 63.7 | 55.3 | -8.4 |
| 6 | 133 | 16 | 189 | 61.5 | 53.7 | -7.8 |
| 7 | 149 | 18 | 189 | 56.4 | 52.1 | -4.3 |
| 8 | 155 | 18 | 189 | 53.7 | 50.6 | -3.1 |
| 9 | 176 | 22 | 252 | 47.3 | 36.7 | -10.5 |
| 11 | 194 | 26 | 252 | 39.8 | 33.6 | -6.3 |
| 13 | 204 | 24 | 252 | 35.2 | 30.5 | -4.7 |
| 15 | 226 | 27 | 252 | 27.1 | 27.3 | 0.2 |
| 16 | 230 | 27 | 252 | 24.8 | 25.8 | 1.0 |

Huffman coding of English text for 64 values produces about 50% compression, before subtracting header and unique values. For the file alice29.txt (see Table 8), 64 input values require an average of 23.7 unique values (190 bits) with 13.5 repeating values (about 40 header bits) and results in about 5% compression using Huffman coding. By implementing a count of most frequently occurring text chars which are coded in 4 bits, followed by remaining unique values in 8 bits could require 40 fewer bits and yield 13% compression for Huffman coding. This example points out that for small data sets, Huffman coding, though optimal, does not produce the high compression rate that is claimed for examples of text data where the Huffman tree overhead is canceled out by larger amounts of data and can yield greater than 40% compression.

Fixed bit coding yields less than 1% compression of English text. However, using text mode, alice29.txt is compressed 25% across compressed blocks. This results from replacing an average of 80% of values with a 4-bit code and the other 20% with their 8-bit value. A control bit is generated to choose between the two encodings.

When considering the spectrum of compressible data for 64 input values, fixed bit coding is estimated to be within a reasonable percentage of the compressed result of using Huffman coding.

# Benchmark Data: Fixed Bit Coding and QuickLZ

Although fixed bit coding runs on small data sets, a test bed was configured to make calls with a specified block size over the values in a file to produce compression results across all blocks in that file. For this test, block sizes of 8, 32 and 64 were tested. The fixed bit coding and QuickLZ 1.5.1 Beta 7 benchmark results are shown in Table 7 with megabytes per second to encode and decode, and compression percentage. The program was run multiple times in a programmed loop of 100 on a Mac with a 1 GHz Dual-Core Intel Core M processor. The files were selected from the Squash Compression Benchmark at <https://quixdb.github.io/squash-benchmark/>.

Table : Benchmark Speed (Mbytes/second) and Compression (% of original): Fixed Bit Coding (FBC) and QuickLZ

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| File | FBC 8  MBs/MBs/Cmp | FBC 32  MBs/MBs/Cmp | FBC 64  MBs/MBs/Cmp | QuickLZ  MBs/MBs/Cmp |
| fireworks.  Jpeg | 269/1218/-1.52% | 294/3730/-.37% | 976/4923/-.17% | 625/13677/-.01% |
| alice29.  txt | 150/300/11.0% | 154/286/22.1% | 159/301/24.7% | 180/244/45.1% |
| mr | 236/884/23.9% | 225/1087/44.9% | 275/1273/44.5% | 286/283/52.0% |
| paper-100k  .pdf | 242/853/5.77% | 522/2438/4.30% | 547/2381/5.27% | 395/203/10.2% |
| ptt5 | 240/579/68.3% | 273/895/72.0% | 317/1283/66.6% | 553/743/83.1% |
| Sum | 144/554/11.1% | 164/637/18.8% | 206/1033/16.1% | 277/326/51.7% |

For the most part, FBC compression speed is fastest for 64 values and slowest for 8. Overhead is a large portion of compression time for small numbers of values due to management of many small blocks. For FBC 64, there are 7/8 fewer bits than for FBC 8 to indicate whether the data compressed or not. The higher compression of 64 bits means that more time was spent processing blocks, which reduces execution speed.

Fixed bit coding decompresses files with compressed data 1.2 (alice29.txt) to 10 times faster (paper-100k.pdf) than QuickLZ. The data format for fixed bit, text mode and single value mode algorithms requires very little processing. Fixed bit compression takes up to 2 times longer to compress than QuickLZ. FBC 64 compression rate is at least half that of QuickLZ except for the file sum at only 30%. When considering that comparison is between blocks of 64 and an entire file, these results make fixed bit coding a viable tool for compression of small data sets.

By uncommenting the GEN\_STATS macro in the source code, details about the data are printed, including number of uncompressed blocks and the distribution of number of unique values in compressed blocks. The random data in much of the file means that compression is stopped quickly when the 3, 7, or 16 maximum unique values for 8, 32, or 64 input values is reached. For fireworks.jpeg, over 99% of blocks were incompressible. This helps produce the high decompression speed. The incredibly fast decompress for fireworks.jpeg by QuickLZ highlights that fixed bit coding is working on small blocks that must be handled individually rather than for an entire file.

## Fixed Bit Coding with Minimal Text Data

In mr for FBC 64, the average number of unique values is 7.11, ranging from 2 to 16, Encoding 4 bits is most time-consuming, and 1/3 (FBC 8) to 1/2 (FBC 64) of blocks were compressed. ptt5 compresses 86% (FBC 8) to 89% (FBC 64) of blocks. These have 2 to 3 unique values, and result in high-speed compression.

In the file sum, 30% (FBC 8) to 46% (FBC 64) of blocks are compressed. The average number of unique values for 64 input values is 12. When too many unique values occur and they are interspersed with zeros, this lengthens compression time for incompressible blocks. The data in this file is compressible by 5.45% for 2-byte blocks, 8.77% for 8-byte blocks, and 11.9% for 64-byte blocks. This shows that even very small data sets can sometimes be compressed.

## Text Data

Without text mode, English text cannot be compressed by fixed bit coding. The algorithm limits the overhead of text mode to 10% to 20% by testing as few data values as is reasonable. For the file sum (FBC 64), 1/3 of compressed blocks are text mode and most of the remaining blocks use 4-bit encoding, which slows compression time. For paper-100k.pdf (FBC 64), 72% of the compressed data is text, but with 90% of the data incompressible, the file is processed quickly. Text mode, at 25% compression, is less preferred than 4-bit encoding, which often produces greater than 30% compression. Data that contains repetitions of the letter ‘a’ might be compressible with 2 or 3 bits and have a much higher compression ratio than text. Although text mode is tested first, small numbers of unique values pass through to the standard fixed bit coding algorithm.

Looking at the compression speed for alice29.txt, you can see that both fixed bit coding and QuickLZ have slower compression times than for other file types. On average, text data contains 24 unique values in 64 input values. For fixed bit coding, the algorithm to encode text characters is slightly more involved than for encoding fixed bit values.

## Single Value Data

In the file mr (FBC 64), 37% of blocks are compressed using single value mode because most of these contain repeating 0s and all have more than 16 unique values. The file sum (FBC 64) has 11% of blocks compressed using single value mode. Both of these files point out the necessity to augment the fixed bit coding algorithm to handle compressible blocks with more than the supported number of unique values. Although multiple values are sometimes compressible, the tradeoff of time and rate of compression eliminates them from the algorithm.

# Conclusion

This paper has shown that fixed bit coding produces compression ratios that approach those of Huffman coding, which is the optimal frequency-based algorithm. To make compression viable for small data sets, fixed bit coding bypasses data that cannot be compressed by 25% to limit the time spent checking incompressible data. With text mode, English text can be compressed 25%. The single value mode adds compression of data with a frequently occurring single value plus more unique values than the number of input values supports in fixed bit coding. Along with the resulting extremely fast compression and decompression speeds, the fixed bit coding algorithm is the only known candidate for applications that could benefit from high-speed compression of small data sets.