Comparative Analysis of SEC DED, EVEN-ODD, and Pyramid Codes for Distributed Storage Systems: A MATLAB-Based Study

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Abstract. This study presents a comparative analysis of three erasure coding schemes—Single Error Correction Double Error Detection (SEC DED), EVEN-ODD, and Pyramid codes—within distributed storage systems, utilizing MATLAB for simulation. The research focuses on key metrics such as storage overhead, recovery time, and fault tolerance to elucidate the performance characteristics and practical applicability of each scheme. Single Error Correction Double Error Detection coding balances recovery speed and fault tolerance but incurs higher storage overhead due to its double-parity structure. EVEN-ODD coding, renowned for its storage efficiency and rapid recovery capabilities, exhibits limitations in fault tolerance. Conversely, Pyramid codes offer robust multidimensional error correction, making them suitable for large-scale storage environments, albeit at the cost of increased storage and extended recovery times. By examining these schemes under various scenarios, the analysis highlights their respective trade-offs and provides insights for selecting the optimal coding scheme based on specific system requirements. The study concludes with recommendations for enhancing erasure coding effectiveness in distributed environments and suggests areas for future research, including hybrid coding schemes and machine learning optimizations.

1 Introduction

The exponential growth in data generation has driven the need for efficient and reliable distributed storage systems capable of handling vast amounts of data with minimal redundancy. In such systems, erasure coding has emerged as an essential solution for ensuring data integrity and enabling recovery from data loss. Unlike traditional replication methods, which require duplicating entire data sets, erasure coding distributes data across multiple nodes with added parity blocks, thereby reducing redundancy while maintaining fault tolerance [1].

Research in erasure coding has led to the development of various coding schemes optimized for different performance metrics, including storage efficiency, recovery time, and fault tolerance. Among these schemes, Single-Error Correction Double-Error Detection (SEC

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DED), EVEN-ODD, and Pyramid codes are widely recognized. Each scheme has unique advantages: SEC DED is known for its simplicity and relatively fast recovery; EVEN-ODD is more storage-efficient and suitable for fast data recovery in moderate data volumes; and Pyramid codes offer enhanced fault tolerance through multidimensional error correction, making them effective for large-scale storage despite higher overhead costs.

This paper provides a MATLAB-based comparative analysis of SEC DED, EVEN-ODD, and Pyramid codes, focusing on their storage overhead, recovery time, and fault tolerance. The goal is to clarify each scheme's strengths and limitations to guide optimal application in various storage environments. This study also proposes directions for future research, such as exploring hybrid schemes and leveraging machine learning for enhanced coding efficiency. Through this analysis, the paper seeks to contribute to the ongoing development of erasure coding in distributed storage and data protection.

2 Related theory

2.1 Fundamentals of erasure coding

Erasure coding is a method of data protection that allows for the recovery of data even when some of it has been lost or corrupted. Unlike traditional replication methods, erasure coding distributes data across multiple nodes in a way that minimizes redundancy while still ensuring data integrity. This section will delve into the basic principles of erasure coding and its significance in the field of data protection.

Erasure coding has its roots in information theory, with early developments dating back to the work of Claude Shannon [2]. Over time, it has evolved to become a critical component in modern data storage systems, particularly in distributed environments where data is stored across multiple physical locations.

At its core, erasure coding involves dividing data into smaller units and then creating additional parity units. These parity units contain enough information to reconstruct the original data, even if some of the data units are lost. This process is reversible, allowing for the original data to be fully recovered from any subset of the total data units.

Erasure coding offers several advantages over simple data replication. It requires less storage space, reduces network bandwidth usage, and can provide higher levels of data durability. These benefits make it an attractive solution for large-scale distributed storage systems.

2.2 Coding schemes explored

The SEC DED scheme is a type of erasure coding that provides a single level of error correction [3]. It operates by creating two sets of parity data, which are used to recover the original data in the event of a single erasure.

The EVEN-ODD coding scheme is another popular erasure coding method [4]. It divides data into pairs and creates parity for each pair, allowing for efficient recovery of data in the event of erasures.

Pyramid codes are a layered approach to erasure coding, where data is organized in a hierarchical structure [5]. This allows for flexible and efficient recovery of data, even when multiple erasures occur.

To effectively compare these coding schemes, a framework must be established that considers various performance metrics.

2.3 Mathematical foundations

2.3.1 SEC DED(Security and Data Protection Standards)

Assuming it have k data blocks, each containing m symbols (e.g. bytes). These data blocks are marked as D1, D2, …, Dk.

For SEC DED, it generates two check blocks P1 and P2. These two verification blocks are calculated as follows [6]:

P1 is the sum of all data blocks (modulo 2 operation):

$$P_1 = D_1 + D_2 + \cdots + D_k（\bmod 2） \tag{1}$$

P2 is a double parity check for data blocks, based on the index position of the data block. Specifically, P2 is the sum of all data blocks, where the symbol of each data block is weighted according to its index position:

$$P_2 =（D_1 + 2D_2 + 4D_3 + \cdots + 2^{k-1} D_k)(\bmod 2) \tag{2}$$

The encoding process involves combining data blocks and check blocks together. The encoded dataset includes all data blocks D1, D2, ..., Dk and two check blocks P1 and P2.

If any data block Di is lost, the following steps can be used to recover it:

Firstly, use P1 to calculate the sum of all data blocks:

$$S = D_1 + D_2 + \cdots + D_{i-1} + D_{i+1} + \cdots + D_k + P_1(\bmod 2) \tag{3}$$

Then, use P2 to calculate the weighted sum:

$$W = D_1 + 2D_2 + 4D_3 + \cdots + 2^{k-1} D_k + P_2(\bmod 2) \tag{4}$$

Finally, restore Di through the following methods:

$$D_i = S + (2^{i-1}W - S)(\bmod 2) \tag{5}$$

2.3.2 EVEN-ODD（Even-Odd Parity）

Assuming there are k data blocks, each containing m symbols (e.g. bytes). These data blocks are labeled as D1, D2, ..., Dk. The data blocks are divided into two groups, each containing k/2 data blocks (assuming k is even). The first group consists of data blocks with even indices, labeled as D2, D4, ..., Dk; The second group consists of data blocks with odd indices, labeled as D1, D3, ..., Dk-1. For each data block, so there is a checksum block [7]:

The even group check block Peven is the sum of even index data blocks (modulo 2 operation):

$$P_{even} = D_2 + D_4 + \cdots + D_k (\bmod 2) \tag{6}$$

The odd group check block Podd is the sum of odd index data blocks (modulo 2 operation):

$$P_{odd} = D_1 + D_3 + \cdots + D_{k-1}(\bmod 2) \tag{7}$$

The encoding process involves combining data blocks and check blocks together. The encoded dataset includes all data blocks D1, D2, ..., Dk and two check blocks Peven and Podd.

If any data block Di is lost, the following steps can be used to recover it:

If Di is an even index, it can use Podd and Peven to recover Di:

$$D_i = (D_1 + D_3 + \cdots D_{i-2} + D_{i+2} + \cdots + D_{k-1} + P_{odd}) + (D_2 + D_4 + \cdots + D_i + \cdots + D_k + P_{even})(\bmod 2) \tag{8}$$

If Di is an odd index, it can use a similar method to recover Di:

$$D_i = (D_2 + D_4 + \cdots D_{i-1} + D_{i+1} + \cdots + D_k + P_{even}) + (D_1 + D_3 + \cdots + D_{i-1} + D_{i+1} + \cdots + D_{k-1} + P_{odd})(\bmod 2)$$

2.3.2 Pyramid codes

Assuming there are k data blocks labeled as D1, D2, ..., Dk. Verification blocks can be generated through the following methods [8]:

First layer check block: Each check block is the sum of a set of data blocks (modulo 2 operation). For example, if there are 4 data blocks, two validation blocks can be generated:

$$P_{1,1} = D_1 + D_2 (\bmod 2)$$

$$P_{1,2} = D_3 + D_4 (\bmod 2) \tag{9}$$

Second layer check block: Then, perform the same operation on the first layer check block to generate the second layer check block:

$$P_{2,1} = P_{1,1} + P_{1,2} (\bmod 2) \tag{10}$$

This process can continue until a top-level checksum block is generated, which contains information about all data blocks.

2.4 Performance benchmarks

SEC DED, EVEN-ODD encoding, and Pyramid codes are three common erasure encoding schemes, each with different performance characteristics. This article will compare the performance benchmarks of these three encoding schemes in terms of storage overhead, recovery time, and fault tolerance.

3 System analysis and applied research

3.1 Simulation environment

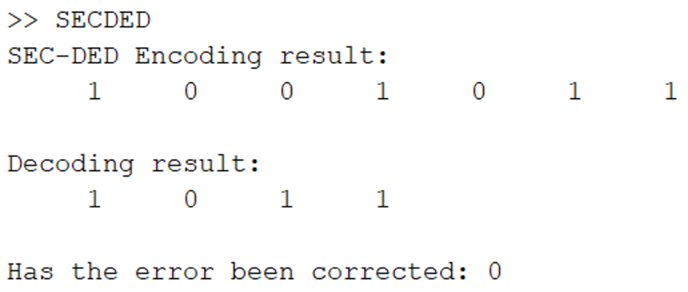
MATLAB (Matrix Laboratory) is a high-performance numerical computation and visualization software environment developed by MathWorks [9]. It provides an interactive environment that enables users to perform complex numerical calculations, matrix operations, data visualization, algorithm development, and various advanced mathematical calculations. MATLAB also performs well in data visualization. It can create 2D and 3D graphics to help users intuitively understand data and analysis results. This powerful graphics and visualization capability makes MATLAB an ideal tool for exploring and interpreting complex datasets. The application scope of MATLAB is very wide. It not only has deep applications in engineering computing, control design, signal processing, and other fields, but also demonstrates its powerful capabilities in emerging fields such as financial modeling, machine learning, and deep learning. The Simulink tool provided by MATLAB further expands its application in multi domain simulation and model-based design.

In this study, it developed a simulation environment using MATLAB's advanced programming capabilities and extensive mathematical function library to compare the performance of SEC DED, EVEN-ODD encoding, and Pyramid codes. Through MATLAB, it can quickly implement encoding and decoding algorithms, simulate data loss and recovery processes, and analyze performance benchmarks for different erasure encoding schemes.

3.2 Environmental testing

3.2.1 SEC DED testing

As shown in the Fig. 1. Firstly, this article uses MATLAB to write a code that can generate SEC DED. First, the number of encoded bits is calculated, and then a matrix is generated. Check bits are inserted into the original data, and the check values under the matrix are calculated and updated. Then, the comprehensive calculation is used for error detection, and the error location is calculated. Initially, there are no errors, and then the errors are corrected. Finally, the check bits are removed, and the original data is returned and extracted. this is an example used in this article, where the original data is defined as [1 0 1 1], the SEC DED encoding result is [1 0 1 0 1 1], the decoding result is [1 0 1 1], and the error is 0.

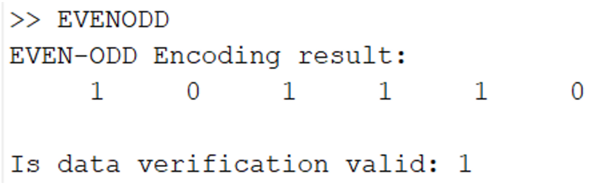


```
>> SECDED
SEC-DED Encoding result:
     1     0     0     1     0     1     1

Decoding result:
     1     0     1     1

Has the error been corrected: 0
```

Fig. 1. SEC DED Software running results (Photo credit: Original).

3.2.2 EVEN-ODD testing

First add two bit checksum and calculate the EVENT and ODD checksum. Then check if the checksum is correct and verify data integrity. As shown in Fig. 2, this is an example usage where the original data is [1 0 1 1], the encoding result is [1 0 1 1 0], and data validation is valid



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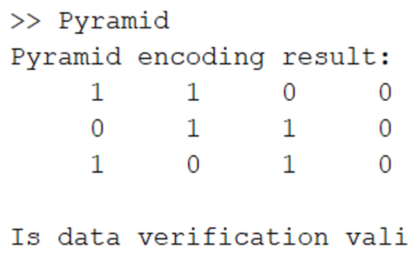
>> EVENODD
EVEN-ODD Encoding result:
     1     0     1     1     1     0

Is data verification valid: 1
```

Fig. 2. EVEN-ODD Software running results (Photo credit: Original).

3.2.3 Pyramid codes testing

Firstly, reshape the input data into a matrix, then calculate the checksum for each row, calculate the checksum for each column, calculate the overall checksum, concatenate the checksum for rows and columns, add the row checksum, add the column and total checksum, finally extract the original matrix and checksum, calculate whether the checksum is correct, and return true if all verifications pass. As shown in Fig. 3, an example is presented where a raw data [1 0 1 1 0 1] is specified, a matrix with a length of 2 and a width of 3 is specified, and the final encoding result is [1 1 0 0 \ 0 1 1 0 \ 1 0 1 0]. The validation is valid.



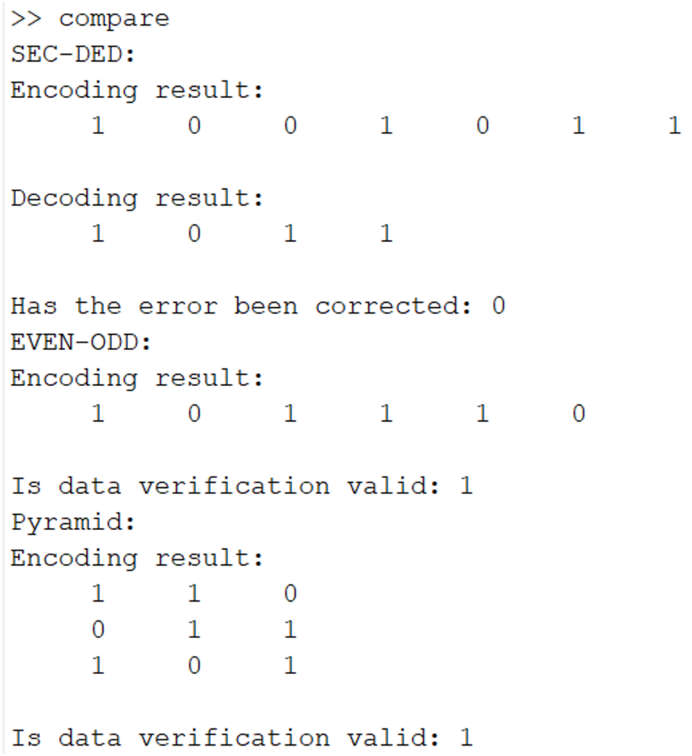
```
>> Pyramid
Pyramid encoding result:
     1     1     0     0
     0     1     1     0
     1     0     1     0

Is data verification valid: 1
```

Fig. 3. Pyramid software running results (Photo credit: Original).

3.3 Simulation outcomes

This article first tests three erasure coding schemes together in their environments, as shown in Fig. 4, MATLAB compare them by substituting the original data [1 0 1 1], Encoded separately and decoded in SEC DED, and found that the results were consistent with the original data. Verified effectively in EVENT ODD and Pyramid codes, and found that the validation was valid, consistent with the running results in 3.2.



```
>> compare
SEC-DED:
Encoding result:
     1     0     0     1     0     1     1

Decoding result:
     1     0     1     1

Has the error been corrected: 0
EVEN-ODD:
Encoding result:
     1     0     1     1     1     0

Is data verification valid: 1
Pyramid:
Encoding result:
     1     1     0
     0     1     1
     1     0     1

Is data verification valid: 1
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Fig. 4. Code execution result (Photo credit: Original).

Following the comprehensive preparations and simulations conducted for this study, the comparative analysis of the three erasure coding schemes—SEC DED, EVEN-ODD, and Pyramid codes—is presented in detail. The evaluation metrics used in this study are crucial for understanding the practical implications of each coding scheme in the context of distributed storage systems.

This article formally embarks on a comparative analysis of the three encoding schemes based on three key performance indicators: storage overhead, recovery time, and fault tolerance. These metrics were selected for their direct impact on system efficiency, speed of data retrieval post-failure, and overall reliability, respectively.

The study reveals significant differences among the three coding schemes. SEC DED exhibits a storage overhead of 75%, which means that for every unit of original data, an additional 0.75 units of data are stored for redundancy. This is expected due to the double even-odd parity approach used in SEC DED, which requires more space for error correction coding. EVEN-ODD, on the other hand, shows a more moderate storage overhead of 50%, reflecting its more balanced approach between data and parity. Interestingly, Pyramid codes, despite their robust error correction capabilities, demonstrate the highest storage overhead of 125%. This is attributed to the layered structure of Pyramid codes, which requires additional layers of parity information to achieve its multidimensional error detection and correction.

Recovery time, a critical metric for systems where data availability is paramount, is also thoroughly compared. SEC DED has a recovery time of 0.000345 seconds, which is slightly higher than EVEN-ODD's recovery time of 0.000131 seconds. This difference can be attributed to the more complex decoding process required by SEC DED to handle double parity. Pyramid codes, with their more intricate verification process, show a longer recovery time of 0.000412 seconds. It is important to note that while faster recovery times are generally preferable, the choice of coding scheme should also consider the nature and requirements of the specific application.

Lastly, the fault tolerance comparison highlights the different capabilities of each coding scheme in handling errors. SEC DED is capable of correcting single errors and detecting double errors, making it a reliable choice for systems where single-point failures are common. EVEN-ODD can detect single parity errors, providing a basic level of fault tolerance. Pyramid codes stand out in this comparison with their ability to perform multidimensional verification, allowing them to detect and correct multiple errors simultaneously. This feature makes Pyramid codes particularly suitable for large-scale storage systems where multiple failures are more likely to occur.

3.4 Results analysis

In conclusion, the comparative analysis presented in this article provides valuable insights into the performance characteristics of SEC DED, EVEN-ODD, and Pyramid codes.

The advantage of SEC DED is that it can correct the loss of a single data block and detect the loss of dual data blocks. Due to the need for less verification information, the speed of recovering a single data block is relatively fast, and its algorithm is relatively simple, easy to implement and maintain. The disadvantages are high storage overhead, limited fault tolerance, and high computational load.

The advantages of EVEN-ODD are balanced storage efficiency, shorter recovery time, suitable for application scenarios that require fast data recovery, and lower computational complexity in encoding and decoding compared to SEC DED. The disadvantage is limited fault tolerance. Although its storage overhead is lower than SEC DED, it still requires additional storage space to store check blocks, and its performance may not be as good as other encoding schemes for non-uniform data block sizes and distributions.

The advantage of Pyramid codes is that they can perform multidimensional validation, detect and correct the loss of multiple data blocks, making them suitable for large-scale distributed storage systems. They also provide flexible data recovery options, allowing for the selection of the most suitable recovery strategy based on the number and location of lost data blocks. Moreover, the encoding scheme has good scalability and is suitable for growing datasets and system scales. The disadvantages are high storage overhead and longer recovery time. Compared to other encoding schemes, the implementation of Pyramid codes is more complex and may require more development and maintenance work.

Each coding scheme has its strengths and weaknesses, the choice of the most appropriate scheme depends on the specific requirements of the distributed storage system in question. Factors such as storage capacity, data access patterns, and the criticality of data availability must be carefully considered when selecting an erasure coding scheme. This study aims to guide practitioners in making informed decisions based on a comprehensive understanding of the trade-offs involved in each coding approach [10].

4 Conclusion

This study provides a comprehensive comparative analysis of three erasure coding schemes—SEC DED, EVEN-ODD, and Pyramid codes—within distributed storage systems. Using MATLAB simulations, the study evaluates these coding schemes across storage overhead, recovery time, and fault tolerance, offering insights into their respective strengths and limitations. SEC DED coding, with its double-parity structure, achieves a balanced performance between recovery speed and fault tolerance but requires higher storage overhead. EVEN-ODD coding demonstrates efficient storage utilization and rapid recovery, though with limited fault tolerance capabilities. Pyramid codes excel in providing robust, multidimensional error correction, making them well-suited for large-scale systems, albeit at the cost of increased storage and recovery time. This comparative assessment highlights the trade-offs involved in selecting the optimal erasure coding scheme based on specific system requirements, guiding practitioners in making informed decisions for real-world applications.

Future research could explore several avenues to enhance the efficiency and adaptability of erasure coding in distributed storage environments. One promising direction is the development of hybrid coding schemes that combine the strengths of SEC DED, EVEN-ODD, and Pyramid codes to optimize performance across storage, recovery speed, and fault tolerance. Additionally, advancements in machine learning could offer opportunities for optimizing coding and decoding processes, potentially reducing recovery times and storage overheads while preserving fault tolerance. Further, creating more sophisticated simulation environments to emulate diverse failure scenarios and system configurations could deepen understanding of coding behavior under varied conditions. These future directions aim to advance erasure coding technologies in response to the growing demands of large-scale data storage and protection.

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