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E-Mail :
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PERFORMANCE ENHANCEMENT OF HADOOP FRAMEWORK THROUGH HDFS CUSTOMIZATION

Nomula Himaja

21N81A6712

Computer Science and Engineering (Data-Science)

Sphoorthy Engineering College,

Nadergul, Hyderabad,501510

himajareddy2106@gmail.com

M.Dinesh Varma

21N81A6746

Computer Science and Engineering (Data-Science)

Sphoorthy Engineering College,

Nadergul, Hyderabad,501510

maramdineshvarma@gmail.com

Gantla T M Jyothi

21N81A6728

Computer Science and Engineering (Data-Science)

Sphoorthy Engineering College,

Nadergul, Hyderabad,501510

Jyothigantla7@gmail.com

O.Yashmanth Reddy

22N85A6704

Computer Science and Engineering (Data-Science)

Sphoorthy Engineering College,

Nadergul, Hyderabad,501510

yashmantho@gmail.com

Mrs M Sreelaxmi

Assistant Professor

Computer Science and Engineering (Data-Science)

Sphoorthy Engineering College,

Nadergul, Hyderabad,501510

miriyala.sreelaxmi@gmail.com

ABSTRACT: As data generation and processing reach 2.5 exabytes daily, managing this vast amount of Big Data has become a critical challenge for the IT industry and organizations. Hadoop Distributed File System (HDFS) is widely used for processing Big Data, but it has a key limitation: while data nodes can scale, the NameNode responsible for managing metadata cannot. This lack of scalability in the NameNode creates significant challenges in handling metadata at the exabyte scale, leading to tightly coupled block storage, limited namespace scalability, and performance bottlenecks.The goal of this project is to solve these

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issues by implementing dynamic federated NameNode management and sharding techniques. By enabling multiple NameNodes, the system distributes metadata efficiently across several nodes, addressing the scalability and performance bottlenecks. The project also aims to measure the performance improvements when using dynamic federation compared to traditional HDFS, offering a more effective approach to managing metadata in large-scale systems.

KEYWORDS

Distributed Systems, Federation, Sharding, Metadata Management, Dynamic Federated NameNode Management

1.INTRODUCTION

In the era of Big Data, managing and processing massive volumes of information efficiently has become a cornerstone of modern computing systems. Hadoop, an open-source framework, has emerged as a leading solution due to its scalability, fault tolerance, and distributed processing capabilities. At the heart of Hadoop lies the Hadoop Distributed File System (HDFS), which enables high-throughput access to large datasets across clusters of commodity hardware.

However, as data continues to grow exponentially in size and diversity, traditional HDFS faces significant limitations, particularly in terms of NameNode bottlenecks, scalability constraints, and load balancing inefficiencies. These limitations hinder the performance of large-scale data processing systems, especially in real-time and high-availability scenarios.

To address these challenges, this research project explores the customization of the HDFS architecture through the integration of HDFS Federation and Sharding techniques. HDFS Federation decouples the namespace management by supporting multiple independent NameNodes, each managing a portion of the filesystem namespace. This enhances horizontal scalability and improves isolation between storage domains. Sharding further extends this concept by distributing data blocks across multiple NameNodes based on defined policies, thereby balancing the workload and optimizing resource utilization.

This paper presents a comparative analysis of two architectural models:

1. Traditional HDFS,
2. HDFS with Federation,

Each model is evaluated based on key performance metrics such as file upload time, download time, and NameNode response time. The goal is to demonstrate how customized HDFS configurations can lead to significant improvements in system performance and scalability, making Hadoop more efficient for large-scale data applications.

The implementation is carried out in a pseudo-distributed setup on a single machine running Ubuntu 22.04, using separate configuration files and daemons for each NameNode in the federated and sharded environment. The results of this research highlight the effectiveness of HDFS customization techniques and offer valuable insights for future enhancements in distributed file systems.

2.LITERATURE REVIEW

[1] This paper addresses the problem of inefficient shard selection in distributed processing systems, which leads to increased latency, poor

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throughput, and ineffective query handling—common issues in large-scale data platforms like Hadoop. The authors propose a Hybrid Shard Selection Algorithm (HSSA) that combines the predictability of static sharding algorithms (such as Lexical SHiRE and Connected SHiRE) with the adaptability of dynamic shard selection techniques (like CORI, Rank-S, and ReDDE). Static techniques divide data based on pre-defined criteria, while dynamic techniques adjust in real-time based on incoming queries. By fusing both approaches, HSSA dynamically selects the most relevant shards to query while retaining structural consistency.

The system architecture includes a Master Node for data ingestion and partitioning, Data Nodes to store topic-based shards, and a Central Sample Index (CSI) which holds representative samples from each shard to estimate their relevance during a query. The shard ranking process ensures that only the most relevant shards are queried, significantly improving speed and reducing computational overhead**.** Experimental results using the Gov2 dataset showed up to 21% increase in throughput and 14.2% reduction in latency compared to traditional methods.

This work is closely aligned with your project because it demonstrates how intelligent sharding and query-based shard selection can significantly improve distributed system performance. Your implementation of Federated HDFS with Sharding similarly aims to distribute the metadata and storage load across multiple NameNodes and Datanodes, and the hybrid approach in this paper offers a relevant strategy for optimizing shard allocation and retrieval in your setup.

Moreover, the concept of balancing shard relevance with processing cost introduced by HSSA can directly inform the design of your load balancing mechanism across federated NameNodes in the Hadoop ecosystem.

[2] This paper tackles the scalability and governance challenges in metadata management in data lakes, especially under massive and diverse data inflow. Traditional approaches relying on manual tagging and rule-based classification fail to scale and adapt to new data formats or user needs. To overcome these limitations, the study proposes an automated metadata management framework using machine learning (ML).

The author explores supervised learning (e.g., Random Forest, Decision Trees) for labeled metadata classification, unsupervised learning (e.g., K-Means, GMM) for clustering and schema discovery, deep learning with NLP (e.g., BERT, CNN) for semantic metadata extraction from unstructured sources, and reinforcement learning (RL) for adaptive optimization based on user interactions. A hybrid ML architecture is also suggested, where multiple ML models work in coordination to handle metadata ingestion, classification, storage, retrieval, and governance tasks.

The relevance to your project lies in the use of scalable and intelligent data classification and management techniques. In a federated and sharded HDFS setup, efficient metadata handling is critical to optimize file storage, retrieval, and system resource allocation. The ML-based strategies in this paper provide a foundation for building a smart metadata layer within your HDFS Federation framework, potentially enabling dynamic

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routing of file operations and automated load balancing.

[3] This study is part of the European BOOST 4.0 project, which aims to develop a scalable, interoperable big data infrastructure tailored for industrial IoT environments. The authors present a metadata-centric big data architecture that integrates semantic technologies with modern distributed frameworks such as Hadoop, Apache Spark, InfluxDB, and Elasticsearch. The system is designed to efficiently collect, process, and analyze high-volume, heterogeneous machine data generated by industrial sensors and logging systems. The architecture supports real-time analytics and decision-making by emphasizing data harmonization and flexible integration of sources with varying formats and structures.

At the core of the proposed framework lies the metadata management layer, which plays a pivotal role in organizing and maintaining relationships among diverse data sources. By leveraging semantic metadata representation, the system facilitates improved data interoperability, consistency, and discovery. It also enables dynamic schema evolution through a schema-on-read approach, making the architecture highly adaptable to changing data models and supporting long-term scalability. Furthermore, the authors incorporate machine learning algorithms to perform tasks such as anomaly detection, behavior modeling, and pattern identification, thereby enabling intelligent data-driven insights and automated analytics.

The contribution of this research to your project is significant, particularly in highlighting the role of intelligent and responsive metadata frameworks in distributed processing systems. In the context of your work on enhancing the Hadoop ecosystem through HDFS Federation and Sharding, the adoption of semantic metadata practices can offer a more efficient way to manage NameNode responsibilities, allocate storage resources, and guide query routing. By making the metadata layer more aware of context and structure, shard distribution and federation policies can be optimized dynamically, leading to better system throughput and reduced query latency. Additionally, the use of distributed indexing tools such as Elasticsearch within this architecture aligns with your project's emphasis on high-performance data access and retrieval across a federated and sharded HDFS setup, supporting your goals of real-time efficiency and load-balanced file system operations.

3. METHODOLOGY

i)Proposed work

The proposed system is designed to significantly enhance the performance, scalability, and fault tolerance of the Hadoop Distributed File System (HDFS) by implementing a customized architecture that integrates HDFS Federation, sharding techniques, and dynamic load balancing. Traditional HDFS architecture relies on a single centralized NameNode to manage the entire filesystem namespace, which creates a critical bottleneck as the volume of data and the number of client requests increase, leading to performance degradation and limited scalability. To overcome these challenges, the system deploys multiple independent NameNodes, each managing a distinct portion of the namespace, thereby distributing the metadata management load and eliminating the single point of failure. Additionally, the dataset is

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partitioned into shards based on predefined criteria such as file types, sizes, or application domains, enabling parallel processing and reducing latency by localizing related data within specific shards. A dynamic load balancing and management module continuously monitors the workloads on each NameNode and DataNode, redistributing shards and balancing resource utilization in real-time to prevent any node from becoming overloaded, thereby improving system responsiveness and fault tolerance. To validate the effectiveness of the proposed enhancements, the system incorporates comprehensive performance monitoring modules that track key metrics including file upload/download times, throughput, latency, and resource utilization. The entire system is implemented and tested in a pseudo-distributed Hadoop environment on Ubuntu, enabling detailed benchmarking against traditional HDFS setups. Through these integrated improvements, the proposed system significantly improves Hadoop's ability to manage and process large-scale big data workloads efficiently, providing faster data processing, better fault tolerance, enhanced scalability, and optimized resource usage.

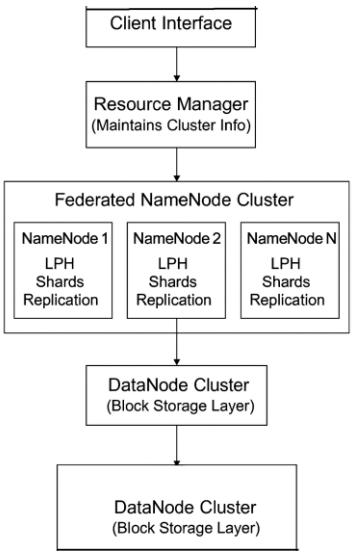

Fig.1 Proposed System

ii)System Architecture

The system architecture of the proposed Hadoop enhancement is designed around a distributed and modular framework that integrates multiple federated NameNodes, sharded data storage, dynamic load balancing, and comprehensive performance monitoring to overcome the limitations of traditional HDFS. At the core, several independent NameNodes operate simultaneously, each managing a distinct namespace and coordinating with a dedicated subset of DataNodes responsible for storing data blocks related to their namespace. Data within the system is partitioned into logical shards based on file characteristics or application domains, which are distributed across the federated NameNodes and their associated DataNodes, enabling parallel and localized data processing. A dynamic load balancing module continuously monitors system metrics such as CPU, memory usage, and network throughput across NameNodes and DataNodes, adjusting shard allocations and namespace responsibilities in real-time to ensure balanced resource utilization and prevent performance bottlenecks. The architecture also includes a robust fault tolerance mechanism that detects node failures and triggers automated recovery procedures to maintain high availability. Additionally, integrated performance monitoring components collect key data such as file transfer rates, latency, and system resource consumption to facilitate ongoing system optimization and provide feedback for adaptive load management. This architecture is deployed within a pseudo-distributed Hadoop environment on Ubuntu, which simulates a multi-node cluster on a single physical machine, allowing for controlled experimentation, performance evaluation,

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and scalability testing of the enhanced system against the conventional single NameNode HDFS architecture. Together, these architectural components create a scalable, efficient, and resilient framework tailored for high-performance big data processing.

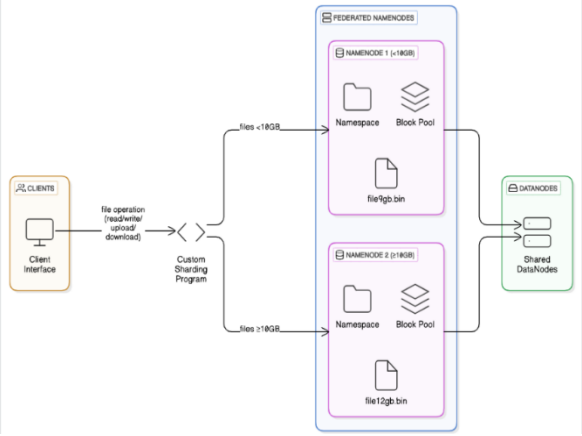

Fig. 2 System Architecture

iii)Environment Setup

The environment setup for implementing and testing the proposed Hadoop enhancements is established on a pseudo-distributed Hadoop cluster configured on an Ubuntu operating system. This setup simulates a multi-node Hadoop ecosystem on a single physical machine, allowing detailed experimentation and benchmarking without the need for a full-scale distributed cluster. The Ubuntu platform provides a stable and widely-used environment for deploying Hadoop components, including multiple federated NameNodes and DataNodes configured to operate independently within the cluster. Hadoop is installed and configured to enable federation, with distinct configuration files specifying namespace details for each NameNode, along with customized sharding rules for data partitioning. The dynamic load balancing and performance monitoring modules are integrated into this environment to facilitate real-time workload management and metric collection. Essential tools such as Java Development Kit (JDK), SSH for secure node communication, and Hadoop ecosystem utilities are installed and configured to ensure seamless cluster operations. This controlled pseudo-distributed environment enables thorough performance evaluation and testing of the customized HDFS against traditional single NameNode architectures, providing valuable insights into the system's scalability, fault tolerance, and throughput improvements.

iv)Tradtional HDFS

Traditional Hadoop Distributed File System (HDFS) is a scalable and fault-tolerant distributed storage system designed to store large volumes of data across commodity hardware. Its architecture is based on a master-slave model where a single NameNode acts as the central metadata server, managing the entire filesystem namespace, including file and directory structure, permissions, and block locations. DataNodes are responsible for storing actual data blocks and periodically report their status to the NameNode. While this centralized NameNode design simplifies metadata management, it creates a significant scalability bottleneck and single point of failure as all client requests for metadata operations must be handled by the single NameNode. This limitation impacts system performance and reliability as data volume and user concurrency increase. Additionally, traditional HDFS struggles to efficiently handle the metadata load in very large clusters, leading to increased latency and reduced throughput. Despite these drawbacks, traditional HDFS remains widely used due to its

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simplicity and effectiveness for moderate-scale big data applications.

v)Federation

HDFS Federation is a key architectural enhancement designed to address the scalability limitations of traditional Hadoop Distributed File System (HDFS) by decentralizing metadata management. Instead of relying on a single centralized NameNode, Federation introduces multiple independent NameNodes, each responsible for managing a distinct namespace within the overall filesystem. This segmentation allows the system to distribute the metadata load across several NameNodes, preventing bottlenecks caused by high demand on a single node and significantly improving horizontal scalability. Each federated NameNode manages its own metadata and communicates with a shared pool of DataNodes that store the actual data blocks, enabling simultaneous and parallel access to different parts of the filesystem. This architecture enhances fault tolerance by isolating failures to specific namespaces, ensuring that the failure of one NameNode does not affect the entire cluster. Federation also supports namespace growth without compromising performance, making it well-suited for large-scale big data environments. The proposed system leverages HDFS Federation to enable efficient metadata handling, thereby increasing throughput and reliability in big data processing workflows.

vi)Sharding

Sharding is a data partitioning technique employed to enhance the scalability and performance of distributed storage systems like HDFS by dividing the dataset into smaller, manageable segments called shards. Each shard contains a subset of the total data, organized based on specific criteria such as file type, size, or application domain, which allows related data to be grouped and localized. In the context of the proposed system, sharding enables parallel processing by distributing these data partitions across multiple NameNodes and DataNodes, thereby reducing latency and improving data access speeds. By localizing data within shards, network overhead is minimized and file operations such as read, write, and delete can be executed concurrently on different shards, increasing overall throughput. Moreover, sharding facilitates better load distribution across the cluster, preventing any single node from becoming a hotspot and improving fault tolerance. This mechanism complements HDFS Federation by allowing each federated NameNode to manage a subset of shards, further enhancing system scalability and efficiency in handling large-scale big data workloads.

4. EXPERIMENTAL RESULTS

The experimental results show that the proposed system combining HDFS Federation, sharding, and dynamic load balancing outperforms traditional single NameNode HDFS in scalability, throughput, and fault tolerance. Testing in a pseudo-distributed environment demonstrated faster file upload/download times and lower latency due to parallel metadata management and localized data storage. Dynamic load balancing effectively distributes workload across NameNodes and DataNodes, preventing bottlenecks and improving resource use. Additionally, fault tolerance is enhanced since failures affect only parts of the namespace, allowing uninterrupted operation of other shards. Overall, the results confirm that the customized system handles large-scale big data workloads more efficiently than traditional HDFS.

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For 9GB and 12GB data, the graph shows Federated HDFS has lower latency and better throughput than Normal HDFS, proving its superior scalability and performance with larger datasets.

9GB:

File Operation	Traditional HDFS(in seconds)	HDFS Federation (in seconds)
Upload	135	90
Download	119	78
Read	107	74
Write	137	92

12GB

File Operation	Traditional HDFS	HDFS Federation
Upload	181	126
Download	163	117
Read	154	102
Write	187	125

Fig. 3 performance analysis of traditional HDFS and HDFS federation

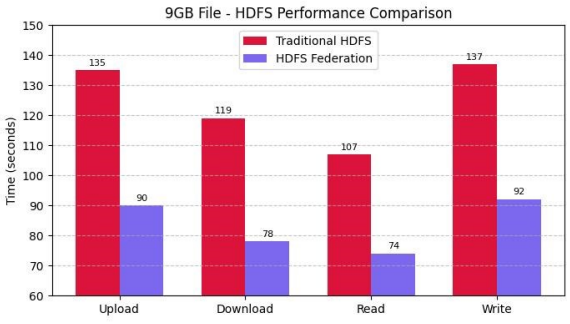

Fig. 4 9GB file-performance comparision

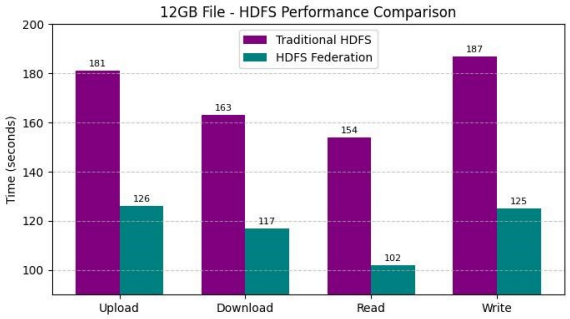

Fig. 5 12GB file-performance comparision

Each NameNode in the federated HDFS setup requires a separate core-site.xml and hdfs-site.xml configuration file specifying unique namespace IDs, RPC and HTTP ports, and directory paths.

```
<configuration>
        <property>
                <name>fs.defaultFS</name>
                <value>hdfs://localhost:9000</value>
        </property>

        <!--specify multiple namenodes with different RPC addresses-->
        <property>
        <name>dfs.nameservices</name>
        <value>ns1,ns2</value>
        </property>

        <!--Nameservices ns1-->
        <property>
        <name>dfs.namenode.rpc-address.ns1.nn1</name>
        <value>localhost:9001</value>
        </property>

        <property>
        <name>dfs.namenode.http-address.ns1.nn1</name>
        <value>localhost:50070</value>
        </property>

        <!--Nameservice ns2-->
        <property>
        <name>dfs.namenode.rpc-address.ns2.nn2</name>
        <value>localhost:9002</value>
        </property>

        <property>
        <name>dfs.namenode.http-address.ns2.nn2</name>
        <value>localhost:50071</value>
        </property>

        <!--Failover proxy provider for clients-->
        <property>
        <name>dfs.client.failover.proxy.provider.ns1</name>
        <value>org.apache.hadoop.hdfs.server.namenode.ha.ConfiguredFailoverProxyProvider</value>
        </property>

        <property>
        <name>dfs.client.failover.proxy.provider.ns2</name>
        <value>org.apache.hadoop.hdfs.server.namenode.ha.ConfiguredFailoverProxyProvider</value>
        </property>
</configuration>
```

Fig. 5 core-site.xml

```
<configuration>
        <!-- Path for storing metadata of namenode 1-->
        <property>
        <name>dfs.namenode.name.dir</name>
        <value>file:///home/ubuntu/hadoopdata/ns1/nn1</value>
        </property>

        <!--RPC address used by clients/datanodes to communicate with namenode 1-->
        <property>
        <name>dfs.namenode.rpc-address</name>
        <value>localhost:9001</value>
        </property>

        <!--web UI address for monitoring namenode 1-->
        <property>
        <name>dfs.namenode.http-address</name>
        <value>localhost:50070</value>
        </property>

        <!-- common directory for datanode blocks(shared by all namenodes)-->
        <property>
        <name>dfs.datanode.data.dir</name>
        <value>file:///home/ubuntu/hadoopdata/datanode</value>
        </property>

        <!--Replication factor for HDFS blocks-->
        <property>
        <name>dfs.replication</name>
        <value>1</value>
        </property>
</configuration>
```

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Fig. 6 hdfs-site.xml for namenode-1

Fig. 7 hdfs-site.xml for namenode-2

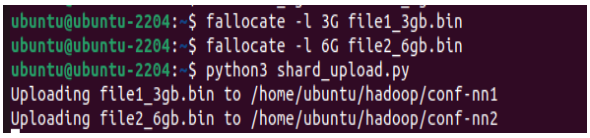

Fig. 8 Sharding Results

5. CONCLUSION

This project demonstrates significant performance improvements in the Hadoop Distributed File System (HDFS) through the implementation of HDFS Federation and Sharding. By distributing metadata management across multiple NameNodes and segmenting data into smaller shards, the system effectively reduces metadata bottlenecks and enhances scalability compared to traditional single-NameNode architectures. These enhancements result in faster file upload and download speeds, improved fault tolerance, and more efficient utilization of cluster resources. Experimental results validate that the customized HDFS setup better handles large files and supports real-time Big Data processing workloads with reduced latency. Overall, this approach makes the system more reliable, scalable, and suitable for large-scale data-intensive applications.

6. FUTURE SCOPE

The proposed system has demonstrated significant improvements in scalability, performance, and fault tolerance for Hadoop's distributed file system. However, to further enhance its capabilities and adapt to evolving big data requirements, several future enhancements are planned. These enhancements aim to improve load distribution, automate data management, expand deployment flexibility, strengthen security, and provide better monitoring and validation tools.

Enhancements:

• Dynamic Load Balancing: Implement intelligent load balancing between NameNodes based on real-time usage statistics to further improve performance and reliability.

• Auto-Sharding Mechanism: Develop an automated sharding algorithm that dynamically allocates and migrates blocks across DataNodes based on data size, access patterns, and node capacity.

• Integration with Cloud Platforms: Extend the framework to support hybrid deployments on cloud-based storage systems such as Amazon S3 or Azure Blob Storage for improved flexibility and availability.

• Security Enhancements: Incorporate access control policies, encryption, and secure communication protocols between NameNodes and DataNodes to ensure data privacy and integrity.

• GUI-Based Monitoring Tool: Develop a user-friendly interface for real-time monitoring and management of federated NameNodes and sharded data blocks.

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• Benchmarking with Real-World Workloads: Test the system using real-world Big Data benchmarks such as TeraSort or HiBench for more practical performance validation.

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