Design of Elastic Distributed KV Store

***Abstract*——**This paper presents the design and implementation of a distributed key-value (KV) store system that supports heavy read workloads while maintaining data consistency during dynamic server additions and removals. The system leverages thread-safe data structures and communication protocols to ensure reliability and scalability. Performance evaluations demonstrate the system's ability to handle dynamic operations effectively, achieving up to 99% accuracy in data consistency and up to 320 operation times per second during server reconfigurations

Keywords: *Distributed systems, Key-value store, Data consistency, Thread-safe structures, Dynamic server scaling, Consistent Hashing, Multi-Thread*

1 Introduction

The aim of this project is to develop an elastic, distributed key-value (KV) store that allows manual addition and removal of servers, managed by a centralized master node. The architecture is designed to optimize scalability and maintain consistency while ensuring efficient interaction between clients and storage servers. The master node serves as the core coordinator, maintaining metadata and directing client requests to the appropriate storage servers based on key locations.

To achieve the project goals, we implemented a multi-threaded architecture for both the master and server sides. This architecture supports seamless communication, dynamic server management, and high-performance data operations, laying the groundwork for a scalable distributed KV store system.

2 Background

Elastic key-value (KV) stores have become integral components of modern distributed systems, especially for cloud-native applications that demand high scalability, availability, and efficient resource management. Amazon's Dynamo[1] was the first large-scale industrial implementation of this model, effectively addressing these challenges while also playing a pivotal role in popularizing key-value stores in both academia and industry. Today, key-value stores are widely used in diverse domains, including distributed caching[2], session storage[3], NoSQL databases for big data[4], blockchain and cryptocurrencies[5], configuration management systems[6], and real-time analytics[7]. These systems store data in a simple key-value format, enabling fast read and write operations [8].

Elastic KV stores are specifically designed to handle dynamic workloads, and they can scale resources up or down based on demand, optimizing resource utilization and reducing operational costs. This elasticity is critical in cloud environments, where workloads are unpredictable and can experience sudden spikes in demand. Elasticity ensures that cloud-native applications can adapt to varying traffic patterns without over-provisioning resources, which can be both costly and inefficient.

Recent advancements in elastic KV store technology further enhance these systems' ability to scale and optimize performance in cloud environments. For example, solutions like ElastMan [9] leverage a combination of feedback and feedforward control to manage resources dynamically in cloud-based KV stores, ensuring optimal performance despite fluctuations in workload and variable cloud virtual machine (VM) performance. ElastMan uses a control framework that dynamically adjusts resource allocation based on real-time feedback, ensuring that performance remains optimal even during periods of high variability.

Similarly, DINOMO[10] extends the capabilities of elastic KV stores by utilizing disaggregated persistent memory (DPM) to separate compute and storage resources. This separation provides greater flexibility in resource management, improving both fault tolerance and performance. DPM allows for more efficient data placement and access patterns, which helps to reduce latency and increase throughput in distributed systems. By leveraging DPM, DINOMO offers an innovative solution for scaling key-value stores in modern cloud architectures, where resource elasticity and fault tolerance are paramount. In addition to these advancements, recent research has explored the integration of machine learning (ML) techniques to further optimize the performance of elastic KV stores. For instance, ML-based resource management frameworks have been proposed to predict and dynamically allocate resources based on anticipated workload changes, ensuring that KV stores can adjust in real time to meet performance requirements[11]. These

frameworks leverage historical workload data and real-time analytics to predict traffic patterns, enabling more efficient scaling decisions.

Moreover, hybrid storage architectures are gaining traction in the development of elastic KV stores. Combining traditional storage technologies with emerging memory systems like persistent memory (PMEM) and storage-class memory (SCM) has shown promise in improving the performance of KV stores. These hybrid storage solutions offer the low-latency benefits of in-memory storage while maintaining the persistence and reliability of traditional disk-based storage, providing a balance between high performance and durability. Hybrid architectures allow elastic KV stores to meet the growing demands of modern applications by enhancing throughput and reducing latency, particularly in write-heavy workloads where data consistency and durability are critical[12].

In addition to storage innovations, research has focused on improving the data consistency models of elastic KV stores. As these systems scale and distribute data across nodes, ensuring consistency while maintaining performance remains a challenge. Traditional consistency models, such as strong consistency, often introduce latency, whereas eventual consistency can lead to data anomalies in highly distributed systems. Newer approaches, like causal consistency and tunable consistency models, provide a middle ground, offering scalability and fault tolerance while minimizing the risks of data inconsistency [13]. These models have been further optimized for elastic KV stores, enabling them to handle the trade-offs between consistency and performance more efficiently.

To support the growing complexity of cloud-native applications, containerization and microservices architectures have also been integrated into elastic KV store solutions. Containerization allows for greater flexibility in deploying and managing KV stores, enabling them to scale more efficiently in cloud environments. By coupling KV stores with container orchestration platforms like Kubernetes, systems can automatically scale, replicate, and distribute data across a fleet of containers, improving resource allocation and fault tolerance [14]. The use of microservices architectures ensures that KV stores can operate independently, providing enhanced scalability and fault isolation while enabling dynamic resource management.

The integration of cloud-native storage solutions such as software-defined storage (SDS) is another area of ongoing development. SDS abstracts the underlying storage infrastructure, enabling more granular control over how data is distributed and accessed across a distributed system. This flexibility supports the dynamic scaling needs of elastic KV stores, ensuring that they can efficiently handle varying workloads and adapt to changes in resource availability in real-time [15].

These continuous innovations, such as the integration of hybrid storage systems, advanced consistency models, machine learning-based resource management, and cloud-native storage solutions, demonstrate the evolution of elastic KV stores. By improving their efficiency, scalability, and adaptability, these advancements make elastic KV stores better suited to meet the demands of modern cloud computing environments and applications that require high performance, low latency, and elastic scalability.

3 System Structure

Figure 1 illustrates the architecture of the distributed key-value store system. The system consists of three main components: the Master Node, the KV store servers, and the Clients.

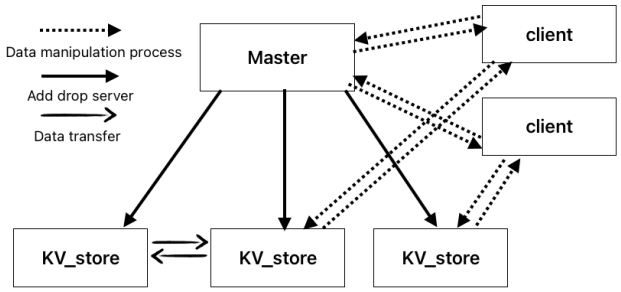

Figure 1: System Architecture of the Distributed Key-Value Store

The Master Node manages system coordination and is responsible for dynamically adding or removing KV store servers to ensure scalability and load balancing. It assigns key ranges to servers and coordinates data migration between servers during server addition, removal. The communication between the master node and the KV store servers is depicted by the solid arrows. The KV store servers are distributed storage nodes that store key-value pairs and directly handle client requests for data manipulation operations, such as read, write, and delete. Clients interact directly with the KV store servers after querying the position of the key from master (represented by the dashed arrows) to reduce latency and improve performance. During critical operations like server addition or removal, the master coordinates data transfer between servers, ensuring data consistency. Mechanisms like the isMigration flag are employed to block write and delete operations during data migrations, allowing only read operations to ensure consistency.

This architecture is designed for scalability, fault tolerance, and high performance, delegating client interac-

tions to the KV store servers while the master node handles metadata and system coordination.

4 MultiThreaded Structure

This section introduces the multi-threaded[16] architecture of the distributed key-value store system, focusing on the internal structures of the `KV store` servers and the `Master Node`. Each component is designed to handle concurrent operations efficiently while ensuring system stability and data consistency. The shared data structures and thread mechanisms are briefly outlined here, with detailed discussions in Section 5 and Section 6.

4.1 KV Store Internal Structure

Figure 2 shows the internal structure of a `KV store` server. Each `KV store` server operates as an independent storage node, designed to handle multiple concurrent client requests and maintain consistency during distributed operations.

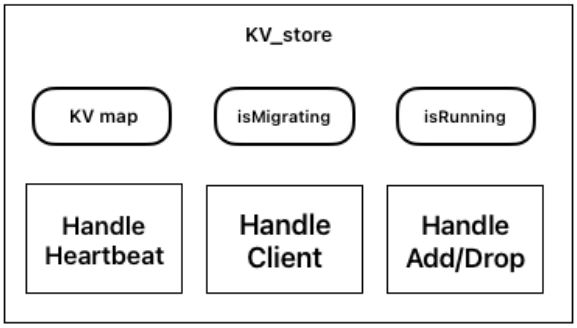

Figure 2: Internal Structure of a KV store Server

The KV map is the central data structure of the server, responsible for managing key-value pairs in a thread-safe manner. The isMigrating flag ensures data consistency during key migrations, allowing only read operations while blocking writes and deletes. The isRunning flag facilitates a graceful shutdown, enabling all threads to complete their current tasks before termination.

The `KV store` employs three primary threads: the handle heartbeat thread communicates with the master node to indicate the health of the server, the handle client thread processes client requests, and the handle add/drop thread manages key range adjustments and migrations during server addition or removal. These components ensure that the `KV store` server operates reliably in a distributed, multi-threaded environment.

4.2 Master Node Internal Structure

Figure 3 illustrates the internal structure of the `Master Node`, which acts as the central coordinator for the distributed system. It manages metadata, ensures consistency, and coordinates operations such as key migrations and server additions or removals.

The master node utilizes three core shared data structures: the consistent hash map, which maps key ranges to servers and enables efficient data distribution; the KV store map, which tracks metadata for all active servers, including their statuses and key ranges; and the migrating list, which records ongoing migrations to prevent conflicts during data transfers.

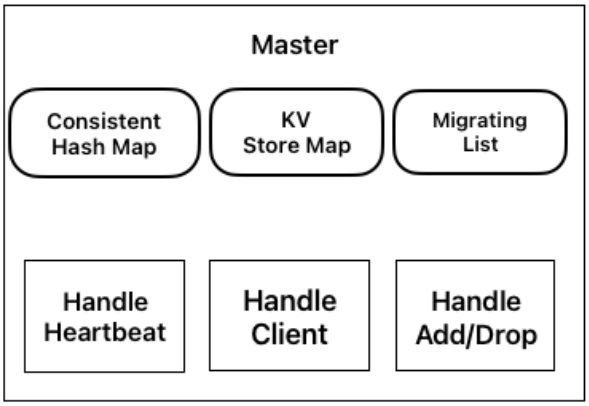

Figure 3: Internal Structure of the Master Node

To handle its responsibilities, the master node is multi-threaded, with dedicated threads for specific tasks. The handle heartbeat thread monitors the health of all servers through periodic heartbeat signals, the handle client thread processes system-level client requests, and the handle add/drop thread manages server additions, removals, and associated key migrations. These threads enable the master node to adapt dynamically to system changes and maintain high availability.

5 Data Structures

The distributed key-value (KV) store system relies on several robust data structures to ensure scalability, fault tolerance, and consistency in a multi-threaded environment. This section describes the key components implemented within the master node and the `KV store` servers. While the functions of these data structures are briefly introduced here.

5.1 KV Store Map, Master Side

The KVStoreMap is a thread-safe data structure in the master node that manages metadata for all KV store servers. It uses a std::shared_mutex [17] to support concurrent reads and exclusive writes, ensuring high performance for read-heavy operations while maintaining consistency during updates.

5.1.1 Structure of the KV Store Map

Each store_id in the KVStoreMap is associated with a JSON-like structure containing server metadata. The structure includes fields such as the server's IP address, ports, key ranges, neighboring servers, and the last heartbeat timestamp. These fields enable efficient management of the system's dynamic topology, as well as fault detection and recovery.

The structure of the JSON value for each store_id is as follows:

```
Key: store_id
Value:
{
  "ip": "",
  "heartbeatPort":"",
  "addDropPort":"",
  "clientPort":"",
  "alive":"true"/"false",
  "keyNum":"",
  keyRange": "",
  "leftStoreId": "",
  "rightStoreId": ""
  "lastHeartbeat: "%Y-%m-%d %H:%M:%S"
}
```

The fields within the JSON value are described below:

- **ip**: The IP address of the storage server corresponding to the store_id. This field is used for connection.
- **heartbeatPort**: The port used for sending and receiving heartbeat signals between the master node and the storage server. This is essential for fault detection and monitoring server health.
- **addDropPort**: The port used for handling server addition or removal operations. It enables the master node to manage scaling events by transferring key ranges or metadata.
- **clientPort**: The port used by clients to interact with the storage server for CRUD (Create, Read, Update, Delete) operations. This ensures direct and efficient communication between clients and servers.
- **alive**: A boolean-like field ("true" or "false") that indicates whether the server is active and operational. The master node updates this field based on heartbeat monitoring and adding or removing a server.
- **keyNum**: The number of keys currently stored in the storage server. This field is used for load balancing and monitoring server utilization, when add or shutting down a server, the master will look up this filed and decide which server should put the key to or from.
- **keyRange**: The range of keys managed by the server.
- **leftStoreId**: The store_id of the adjacent server on the left. This helps maintain the consistent hash ring structure.
- **rightStoreId**: The store_id of the adjacent server on the right. Similar to leftStoreId, this maintains the consistent hash ring.
- **lastHeartbeat**: A timestamp ("%Y-%m-%d %H:%M:%S") indicating the last time the server responded to a heartbeat. This is used to detect inactive or failed servers.

The key functions of KVStoreMap include:

- write(key, value): Inserts or updates a key-value pair in the map.
- read(key): Retrieves the value associated with a given key.
- updateField(key, field, value): Updates a specific field of a key's metadata.
- getStoreKeyNum(key): Provide details about the key count associated with a specific server, which is used to decide which server should remove the key while adding a new server.
- deleteData(key): Removes a key-value pair from the map.

These functions allow the KVStoreMap to perform critical operations such as metadata updates, fault detection, and resource allocation efficiently.

5.2 Consistent Hash Map, Master Side

The ConsistentHashingMap is a thread-safe map that manages the assignment of key ranges to KV store servers. It uses consistent hashing[18] to minimize key redistribution when servers are added or removed. Each hash range is mapped to a store_id, ensuring balanced data distribution and fault tolerance.

5.2.1 Key Functions of the Consistent Hashing Map

The primary functions that implemented of the `ConsistentHashingMap` include:

- `findParticularKey(key)`: Maps a given key to its responsible server by calculating its hash value.
- `addNew(oldRange,newRange,storeId)`: Adds a new server to the hash ring by assigning it a subset of an existing range.
- `removeRange(oldRange, newRange)`: Merges a removed server's range with an adjacent range.
- `displayHashRing()`: Displays all key ranges and their corresponding `store_ids`.

The consistent hashing algorithm ensures efficient key mapping and minimal data movement during server changes, making it ideal for dynamic distributed systems.

5.3 Shared String Vector, Master Side

The `SharedStringVector` is a thread-safe vector that tracks servers involved in data migration. By storing the `store_id`s of servers in migration, it prevents conflicts during concurrent migrations.

5.3.1 Key Functions of the Shared String Vector

- `add(store_id)`: Adds a server ID to the vector, ensuring thread-safe modification.
- `getAll()`: Retrieves all elements in the vector.
- `have(store_id)`: Checks if a specific server ID exists in the vector.
- `remove(store_id)`: Removes a server ID from the vector.

These functions allow the master node to coordinate migration activities efficiently while preventing conflicts between concurrent operations.

5.4 KVMap, KV Store Server Side

The `KVMap` is a thread-safe key-value store that manages data within each `KV store` server. It uses a HashMap as its underlying data structure, with `std::shared_mutex` ensuring thread safety.

5.4.1 Key Functions of the KVMap

- `put(key, value)`: Inserts or updates a key-value pair.
- `get(key, value)`: Retrieves the value associated with a key.
- `remove(key)`: Deletes a key-value pair.
- `contains(key)`: Checks if a key exists in the map.
- `browse()`: Returns a string representation of all key-value pairs.

The `KVMap` forms the backbone of data storage in each server, providing robust support for concurrent operations and synchronization.

5.5 isRunning Flag, KV Store Server Side

The `isRunning` flag is a shared atomic boolean variable used to ensure graceful shutdown of all threads in a `KV store` server. When the flag is set to `false`, threads complete their current tasks and terminate, ensuring no operations are interrupted abruptly.

5.6 isMigration Flag for Data Consistency

The `isMigration` flag is a shared atomic boolean variable used to block write and delete operations during data migration. When set to `true`, only read operations are permitted, ensuring data consistency during critical transfers. After migration, the flag is reset to `false`, resuming all operations.

5.7 Advantages of the Data Structures

These data structures enable dynamic server management, efficient key distribution with minimal data movement, consistency and fault tolerance via shared flags and locking mechanisms, scalable migration tracking, and graceful shutdown in multi-threaded environments. Together, these data structures form a solid foundation for the system.

6 System Communication Protocol

6.1 Client Communication Workflow

This section describes the client communication process in the distributed system, focusing on data query and modification operations. The client interacts dynamically with both the master node and designated storage servers, ensuring efficient and scalable operations.

6.1.1 Master Query and Metadata Retrieval

The client queries the master node to determine the appropriate storage server for a given key:

- **Connection Establishment:** A reliable TCP connection is established using a predefined IP and port. Retry policies with exponential backoff handle connection failures.
- **Request and Response Protocol:** Requests are serialized as JSON objects specifying the operation type (e.g., lookup, read) and key. The master node responds with metadata, including the server's IP and port.
- **Error Handling:** The client handles errors such as connection failures or malformed responses using detailed logs and fallback strategies to maintain availability.

The client and master communication workflow is shown in Figure 4.

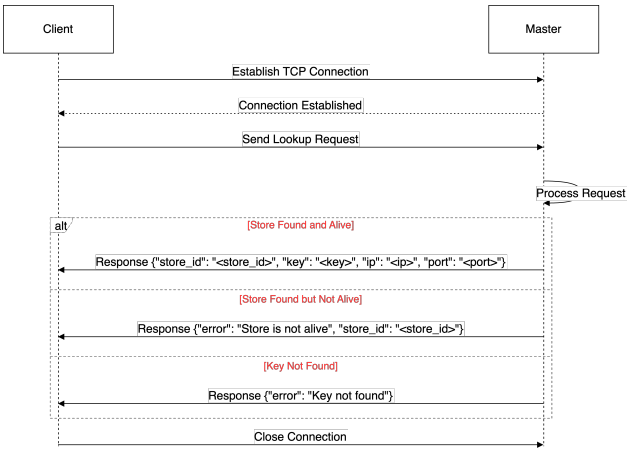

Figure 4: Client-Master Communication.

6.1.2 Direct Server Interaction for CRUD Operations

After receiving metadata, the client interacts with the designated storage server to perform Create, Read, Update, and Delete (CRUD) operations:

- **Direct Connection:** A low-latency connection is established with the storage server, enabling efficient data operations.
- **CRUD Operations:** Structured requests ensure consistent and lightweight communication for optimized performance.
- **Concurrency Support:** A multi-threaded architecture allows each client connection to operate independently, ensuring responsiveness under high traffic.

The client and server communication workflow is illustrated in Figure 5.

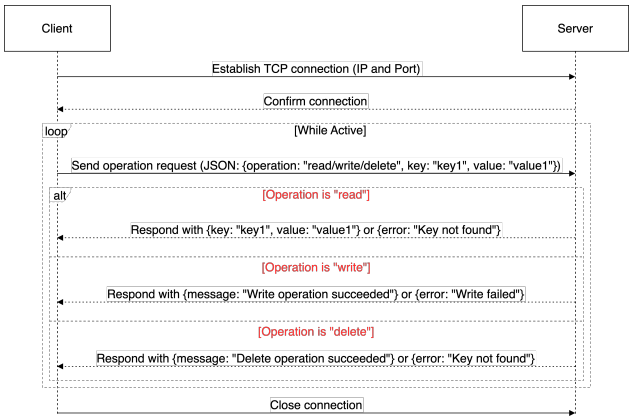

Figure 5: Client-Server Communication.

6.1.3 Error Management

Error-handling mechanisms span both client-master and client-server interactions, including:

- Logging errors for debugging.
- Adaptive retry policies for transient issues.
- Fallback strategies for maintaining availability during failures.

6.2 Server Addition Process

Figure 6 illustrates the process of adding a new server (`KV_store 2`) to the distributed key-value store system. This process ensures that data is redistributed efficiently while maintaining system consistency. The master node coordinates the addition and communicates with the existing and new servers to facilitate the transition.

The server addition process involves the following steps:

1. Starting a New Server: The master node initiates the addition of `KV_store 2` by issuing a system-level `ssh` call to launch the new server process on the target machine. Once initialized, the store server establishes a TCP connection to the master and sends an acknowledgment (`"ack": true`) in JSON format, signaling readiness to join the system.

2. Establishing Connection: Upon receiving the acknowledgment from `KV_store 2`, the master validates

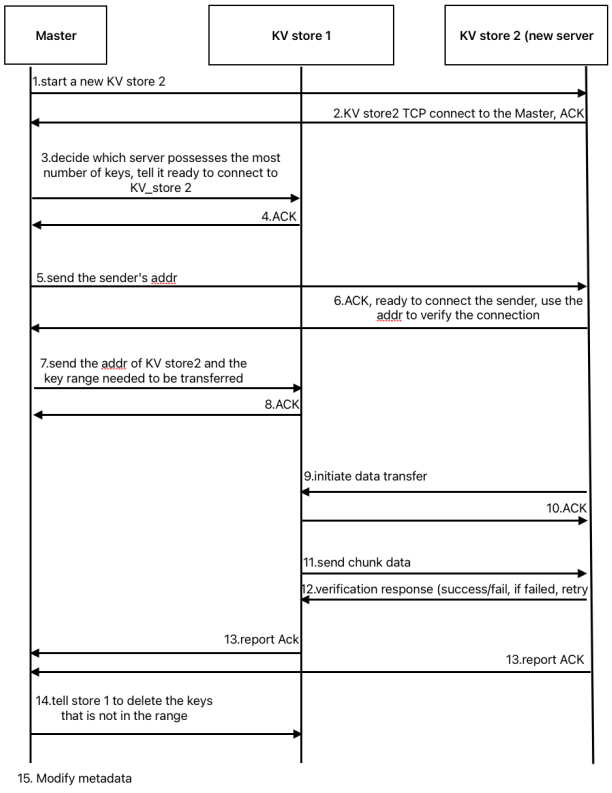

Figure 6: Sequence Diagram for Adding a New Server

the connection through a JSON-based handshake protocol, exchanging metadata such as the server's address and ports. This ensures that the new server is correctly integrated into the system.

3. Assigning Data Transfer: The master node identifies the source server (`KV_store 1`) that possesses the largest key range. A JSON message is sent to `KV_store 1`, instructing it to prepare for data transfer, specifying the target server (`KV_store 2`) and the key range to be migrated. Additionally, both `KV_store 1` and `KV_store 2` are added to the shared vector to ensure that no other migrations involving these servers occur concurrently, preventing conflicts during the data transfer process.

4. Preparing Connection: The source server (`KV_store 1`) initializes the connection with the target server (`KV_store 2`) using the address received from the master. The target server verifies the sender's address and responds with an acknowledgment JSON message, signaling that it is ready to receive the key range.

5. Transferring Data: Data migration begins with the source server (`KV_store 1`) sending key-value pairs to the target server (`KV_store 2`) within the specified key range. Both servers modify their `isMigrating` flags to `true`, effectively blocking any write or delete operations during the migration process to ensure data consistency. Each transferred key-value pair includes metadata such as the key, value, and a checksum for verification. The target server responds with a verification message for each transfer, confirming integrity. If any verification fails, the system retries the transfer until successful.

6. Reporting Completion: Once the entire key range is successfully transferred, both the source server (`KV_store 1`) and the target server (`KV_store 2`) send acknowledgment messages to the master node, confirming the successful completion of the data transfer. The master then updates the metadata in the consistent hash ring and the `KVStoreMap` to reflect the new key distribution and server statuses. Additionally, both `KV_store 1` and `KV_store 2` are removed from the `SharedStringVector` to indicate the completion of their involvement in the migration process.

7. Cleaning Up: The master instructs the source server (`KV_store 1`) to delete keys that are no longer part of its assigned range. This step finalizes the data migration and ensures consistency in the distributed key-value store. Once the cleanup is completed, both the source server (`KV_store 1`) and the target server (`KV_store 2`) modify their `isMigrating` flags to `false`, allowing write and delete operations to resume.

This structured process, combining system-level `ssh` calls for server initialization and JSON-based communication for coordination, ensures smooth server addition while maintaining data integrity and system consistency. Each step in the process is wrapped in a try-catch mechanism to handle potential errors. If an error occurs at any stage, the system rolls back the operation and the involved servers send a `NACK` (Negative Acknowledgment) message to the master node, signaling the termination of the addition process. This error-handling mechanism enhances the robustness of the system and ensures data consistency by preventing incomplete or faulty server additions.

6.3 Server Removal Process

Figure 7 outlines the step-by-step process for safely removing a server (`KV_store 1`) from the distributed system while maintaining data integrity and consistency. This operation involves the master node, the server to be removed, and a destination server (`KV_store 2`) for data migration.

1. Operation Initialization: The master node initiates the removal process by sending a JSON message to `KV_store 1` with the operation type (`"remove_server"`) and the associated server ID. This message establishes a TCP connection between the master node and the server to be removed.

2. Server Acknowledgment: Upon receiving the removal request, `KV_store 1` acknowledges the master's

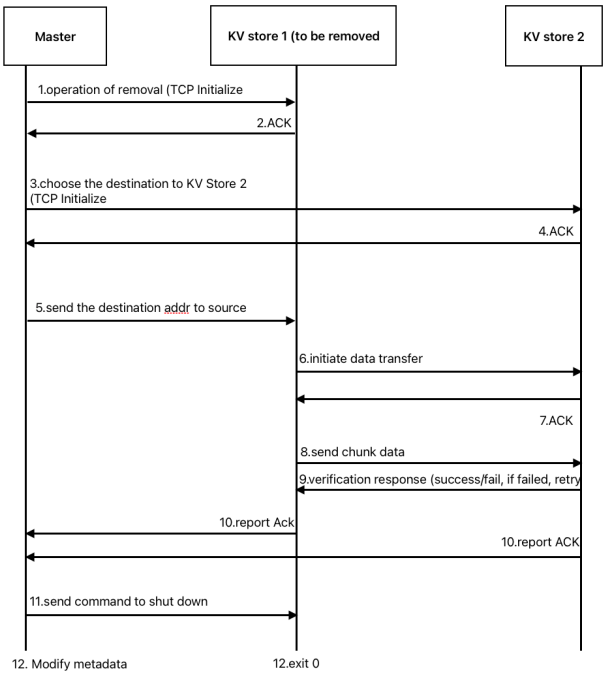

Figure 7: Sequence of Operations for Removing a Server

request by responding with a JSON message containing `"ack": true` and confirming its readiness to proceed.

3. Destination Server Selection: The master node determines the destination server (`KV_store 2`) by utilizing the metadata maintained in the `KVStoreMap`. It identifies the left and right adjacent servers of `KV_store 1` and evaluates their current key counts. The server with the least number of keys is selected as the destination server to ensure balanced data distribution after the removal. A JSON message is sent to `KV_store 2` with the operation type (`"prepare_for_data_transfer"`), signaling it to prepare for the upcoming data migration.

4. Destination Server Acknowledgment: `KV_store 2` acknowledges the data transfer preparation request by responding with a JSON message confirming its readiness and providing its server ID. Upon receiving the acknowledgment, the master node updates the system state by adding both `KV_store 1` and `KV_store 2` to the `SharedStringVector`, marking their involvement in the migration process and preventing conflicts with other ongoing operations.

5. Sending Destination Address to the Source Server: The master node sends the destination address of `KV_store 2` to `KV_store 1`. This message specifies the IP address or hostname of `KV_store 2` and the operation type (`"transfer_data"`). It also includes metadata about the data migration process, such as the specific key range that needs to be transferred to `KV_store 2`.

6. Initiating Data Transfer: `KV_store 1` establishes a connection with `KV_store 2` and initiates the data transfer. The transfer begins with a JSON message of type `"start_chunk_transfer"` containing metadata about the key range to be sent.

7. Destination Server Acknowledgment: `KV_store 2` acknowledges the initiation of data transfer by responding with `"ack": true` to confirm that it is ready to receive the data. Simultaneously, both `KV_store 1` and `KV_store 2` modify their `isMigrating` flags to `true`, blocking write and delete operations to ensure data consistency during the migration process.

8. Sending Data Chunks: The source server (`KV_store 1`) sends the key-value pairs within the given key range, accompanied by a checksum for each chunk to ensure data integrity. Each chunk transfer is accompanied by a `"chunk_data_transfer"` message.

9. Verification and Error Handling: After receiving each chunk, `KV_store 2` verifies the integrity of the data using the checksum. It sends a verification response (`"chunk_verification_response"`) to `KV_store 1`, indicating success or failure. In case of failure, the source server retries the transmission.

10. Completion of Data Transfer: Once all chunks are successfully transferred and verified, `KV_store 1` reports the completion of the data transfer to the master node. Both servers exchange `"data_transfer_complete"` messages to confirm the successful migration.

11. Shutting Down the Source Server: The master node sends a shutdown command to `KV_store 1` with the operation type (`"shutdown"`), instructing it to terminate its processes. Upon receiving this command, `KV_store 1` sets its `isRunning` flag to `false`. This ensures that the server completes all ongoing tasks before shutting down gracefully, preventing data loss or disruption to active operations.

12. Metadata Update: The master node updates the system metadata to reflect the removal of `KV_store 1` and the reassignment of its key range to `KV_store 2`. Specifically, the master removes `KV_store 1` from the consistent hash map and the `KVStoreMap`. It also updates the metadata for `KV_store 2`, adjusting its key number, key range, and left and right adjacent servers to maintain the integrity of the consistent hash ring. Additionally, both `KV_store 1` and `KV_store 2` are removed from the `SharedStringVector`, indicating the completion of the migration process. Finally, the `isMigrating` flags for both servers are set to `false`, allowing normal operations to resume.

This process ensures a seamless and conflict-free removal of a server from the distributed system, maintain-

ing data consistency and fault tolerance throughout the operation. Each step in the process is surrounded by `try-catch` blocks to handle potential errors. If an error occurs at any stage, the system performs a rollback, and the involved servers send `NACK` messages to the master node to terminate the operation, ensuring data consistency and preventing partial or corrupted updates.

6.4 Heartbeats detection

In the system, servers establish a connection with the master node and periodically send heartbeat messages to indicate their active status. This mechanism follows a similar pattern to the Google File System (GFS)[19], where the master communicates with servers through heartbeat messages to maintain system state.

Upon connection, the master assigns a dedicated heartbeat thread to track each server's heartbeat and update its last received timestamp. The master also runs a separate monitoring function at regular intervals (e.g., every 2 seconds) to assess the status of all connected servers. This function filters servers marked as active and checks whether the time elapsed since their last heartbeat exceeds a predefined interval (e.g., 5 seconds). If a server's heartbeat is delayed beyond this interval, its status is updated to inactive.

This dual mechanism—heartbeat tracking and periodic monitoring—ensures prompt detection of inactive servers and maintains system robustness. Figure 8 illustrates the sequence of interactions between the master and a server during heartbeat monitoring.

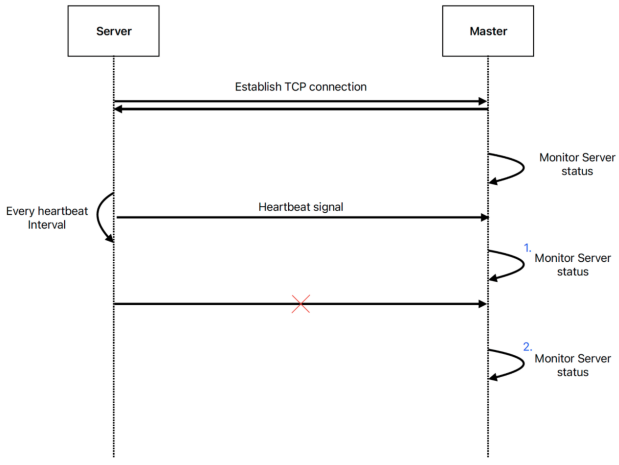

Figure 8: Heartbeat Mechanism for Server Monitoring

7 Performance

The performance of the distributed key-value (KV) store system is evaluated under dynamic and high-load conditions to ensure scalability, fault tolerance, and consistency. The evaluation involves measuring throughput, success rate, and system stability during client requests and server reconfigurations.

7.1 Automated Performance Testing

To thoroughly test the system's performance and reliability, we developed a bash script that automates the following tasks:

- Two bash scripts were designed to evaluate the system's performance under different scenarios:
  - The first script simulates a single client continuously sending requests while the number of store servers dynamically varies between 1 and 10. This script monitors the success rate of client requests to verify the system's reliability and ability to handle dynamic server configurations.
  - The second script spawns 100 client threads simultaneously sending CRUD operations to the system. This script evaluates the system's throughput under varying numbers of store servers, testing its ability to handle high concurrent loads and measuring the throughput performance.

7.2 Performance Metrics

The key metrics collected during the performance tests include:

- **Throughput**: The number of successful requests processed by the system per second.
- **Success Rate**: The percentage of client requests successfully completed, which reflects the system's reliability.
- **System Stability**: The ability of the system to handle server additions and removals without significant degradation in performance or data consistency.

7.3 Results

The results from the automated tests demonstrate the system's ability to:

- Maintain high throughput even under high client load and frequent server adjustments. Tests conducted

with 1, 5, 10, 15, and 20 store servers showed that the throughput remained stable at around 320 queries per second.

- Achieve an average accuracy of over 99.3% for client requests, with failures occurring primarily during write or delete operations during the migration process.
- Maintain 100% system stability during server additions and removals, with no failures observed during testing.

7.4 Analysis

The automated tests reveal several key insights into the system's performance and potential areas for improvement:

- **Master Node Bottleneck:** The master node serves as the central coordinator for all client requests and server operations, managing metadata updates and key range assignments. As the number of clients and store servers increases, the master node experiences a significant increase in workload, leading to slower response times and potential delays in system operations. This centralized architecture limits the system's throughput under high loads.
- **Client-Side Failures During Migration:** Failures in client requests, particularly during write or delete operations, are observed primarily during data migrations. These failures occur because the source or destination server involved in the migration temporarily blocks modify operations to ensure data consistency.

These insights provide a roadmap for future enhancements, ensuring the system continues to scale effectively and maintain high reliability under increasing workloads.

8 Future Work

Our current implementation of the elastic distributed key-value store provides a strong foundation for scalability, fault tolerance, and efficient data operations. However, there are several directions for further improvement and enhancement of the system. These include:

- **RAFT Consensus Protocol**: To ensure data integrity and consistency across duplicate servers, we plan to implement the RAFT consensus protocol. This will allow the system to replicate key-value data across multiple servers, ensuring fault tolerance and maintaining a consistent state even in the event of server failures.
- **Cluster Deployment**: While the current system runs on a single machine for development and testing, we aim to deploy it in a distributed cluster environment. This will involve deploying both the master node and KV store servers across multiple machines, allowing the system to leverage the full potential of distributed computing and increase scalability.
- **Dynamic Server Scaling**: In the future, we plan to implement a dynamic algorithm for automatically adding and removing KV store servers based on system load. This algorithm will monitor factors such as server utilization, request rates, and data distribution to make intelligent decisions on scaling the system dynamically.
- **Client-Side Caching with Update Notification**: To optimize client-server communication and reduce latency, we propose adding a caching mechanism on the client side to store the addresses of KV store servers. A dedicated channel between the master node and clients will be established to notify clients of updates to the key-value mappings whenever servers are added or removed. This mechanism will ensure that clients always have the latest information without having to repeatedly query the master node.

These enhancements will significantly improve the system's scalability, fault tolerance, and performance, making it more suitable for real-world deployment in large-scale distributed environments. By incorporating these features, we aim to further refine the elastic distributed key-value store into a robust and adaptive solution for modern cloud-based applications.

9 Conclusion

In this paper, we proposed a distributed key-value store system designed to handle heavy read operations while maintaining data consistency during server additions and removals. By introducing thread-safe data structures and efficient communication protocols, we ensured the system's reliability and performance. For future improvements, we plan to implement the RAFT consensus protocol to ensure data integrity during server failures and develop a dynamic server scaling algorithm to further enhance the system's performance and scalability.

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