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Master's Thesis

Simulation and Performance of the Raft Consensus Algorithm

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1.Introduction

1.1. Explanation and Background of the Theme

With the continuous development of the Internet and distributed systems, high availability and consistency of data have become the core challenges in the design of distributed systems. Especially in the application of distributed databases, distributed file systems, blockchain and other technologies, consensus algorithms provide a solution that enables multiple computing nodes to reach consensus without global control, thereby ensuring the reliability and consistency of the system. The key issue of consensus algorithm is how to ensure that all normal nodes can still reach a consensus on a certain value and continue to provide services even in the event of some node failures.

Among numerous consensus algorithms, Raft is a relatively novel and widely used consensus algorithm. Raft was proposed by Diego Ongaro and John Ousterhout in 2014 with the aim of providing a more understandable and implementable consensus protocol. Compared to traditional Paxos algorithms, Raft has received widespread attention for its simplicity and clarity. The design of Raft includes three main components: Leader Election, Log Replication, and Log Compaction, and simplifies the complexity of distributed consistency issues through a leader led approach.

The working mechanism of Raft algorithm is more intuitive compared to other consensus algorithms such as Paxos, and its design concept makes it easier for developers to implement and debug consensus protocols in distributed systems. The widespread application of Raft also makes it an important tool for understanding and studying consistency issues in modern distributed systems. However, with changes in cluster size and network conditions, the performance of Raft algorithm remains a topic worthy of further research.

The research object of this paper is the performance of Raft consensus algorithm in different network environments and fault modes, especially its performance in simulation environments, as well as performance indicators such as throughput, latency, and fault tolerance under different loads and node numbers.

1.2. The purpose and objectives of the work

The main purpose of this study is to analyze the performance of the Raft consensus algorithm through simulation experiments, evaluate its performance under various network conditions, node sizes, and failure modes, and explore in depth the applicability of Raft in practical applications. The specific objectives are as follows:

- Performance evaluation: Simulate Raft clusters of different sizes through a simulation environment to analyze the performance of Raft in terms of throughput, latency, and fault tolerance. We will test the impact of different node numbers (such as 3, 5, 7 nodes) and network latency (such as low latency, medium latency, and high latency) on algorithm performance.
- Fault tolerance analysis: Study the fault tolerance of the Raft algorithm when a leader or follower node fails. By simulating node failure scenarios, analyze Raft's recovery capability in situations such as node crashes and network partitioning failures.
- Scalability testing: By increasing the cluster size, explore the performance of Raft algorithm in large-scale distributed systems, especially the overhead in operations such as log replication and leader election. We will pay special attention to Raft's scalability and bottlenecks under high load conditions.
- Comparison and Optimization: In actual testing, compare the performance of Raft with other consensus algorithms (such as Paxos, Zab, etc.), analyze the advantages and limitations of Raft, and explore the possibility of optimizing Raft algorithm in specific application scenarios.

Through these objectives, we aim to provide performance optimization strategies for distributed systems using the Raft algorithm and provide more detailed performance data support for engineers in academia and industry to help them make more appropriate architectural decisions.

1.3. The correlation and potential significance of the results

With the popularization of large-scale distributed systems and the development of technologies such as cloud computing and blockchain, how to design efficient and reliable consistency protocols has become a key issue that many system architects and engineers need to solve. The Raft algorithm has become one of the popular consensus algorithms due to its simplicity and comprehensibility, and has been applied in multiple practical systems such as etcd, Consul, RethinkDB, etc. However, although Raft performs well in many small or medium-sized systems, its performance and scalability still face certain challenges when facing large-scale nodes and high loads. Therefore, a deep understanding of Raft's performance in different environments is of great significance for optimizing its application in practical systems.

This study provides detailed performance data through simulation experiments, which can not only help developers evaluate the performance of Raft algorithm under different conditions, but also provide valuable references for the design of distributed systems. For example, in high latency network environments, the performance of Raft may be greatly affected, so it may be necessary to optimize the Raft algorithm or choose other more suitable consensus algorithms in these environments. On the other hand, for large-scale distributed systems, the scalability bottleneck of the Raft

algorithm is also worth paying attention to. How to ensure the efficiency of the Raft algorithm in large-scale clusters is an important direction for future research.

In addition, the results of this study have guiding significance for the architecture design of practical systems. By analyzing the performance of the Raft algorithm under different loads, fault scenarios, and network conditions, system architects can select appropriate algorithm parameters based on actual needs to optimize the system's throughput and fault tolerance. For example, in environments where node failures occur frequently, it may be necessary to increase the number of nodes or introduce additional fault-tolerant mechanisms to ensure that the system can maintain high availability and consistency even in the event of partial node failures.

In summary, the performance research of Raft consensus algorithm has important theoretical and practical significance for improving the efficiency, reliability, and scalability of distributed systems. Through in-depth analysis of the performance of Raft algorithm in different environments, this article provides theoretical basis and practical experience for the design and optimization of distributed systems, and also provides reference for future research directions of consensus algorithms.

2. Main concepts

2.1. Introduction

2.1.1. Background and Motivation

With the rapid development of information technology, especially the widespread application of cloud computing, blockchain, and big data technology, distributed systems have become a core component of modern computer science and engineering. In a distributed system, multiple nodes collaborate through a network to complete tasks together. One of the core issues of these systems is how to ensure consistency and high availability between different nodes without relying on a single central control. This consistency guarantee is crucial for scenarios such as distributed databases, file systems, and real-time applications.

In distributed systems, consensus algorithms are the foundation for achieving consistency. The main task of consensus algorithm is to ensure that multiple nodes in the system can reach a consensus on a certain value when facing problems such as network delay and node failure, thereby ensuring the correctness of the system state. Classic consensus algorithms, such as Paxos, have been proven to be correct in theory, but due to their implementation complexity, they are often difficult to widely apply in practice.

In order to simplify the understanding and implementation of consensus algorithms, Diego Ongaro and John Ousterhout proposed the Raft algorithm in 2014. The design goal of Raft is to provide a consensus protocol that is easy to understand

and implement, especially suitable for distributed systems that require high availability and consistency. The Raft algorithm simplifies processes such as leader elections and log replication, making it easier to implement compared to Paxos while maintaining a high degree of fault tolerance.

With the widespread application of Raft, how to evaluate its performance in different environments and conditions has become a problem worthy of in-depth research. Especially in large-scale distributed systems, the scalability and fault tolerance of the Raft algorithm, as well as its performance under high loads, network latency, and node failures, are important questions that urgently need to be answered. Therefore, conducting simulation and performance analysis of the Raft algorithm can not only help us gain a deeper understanding of its characteristics, but also provide guidance for practical applications.

2.1.2. Overview of Raft Consensus Algorithm

Raft consensus algorithm is a consensus protocol that has gained widespread attention by simplifying the implementation process. Compared to Paxos, Raft places greater emphasis on implementation clarity and comprehensibility, making it more intuitive for developers to implement and debug. The core components of the Raft algorithm include Leader Election, Log Replication, and Log Compaction.

- Leader election: The nodes in the Raft cluster are divided into three roles: leader, follower, and candidate. Only one node can serve as the leader at a time, and all client requests must be processed through the leader. When the leader fails or the cluster starts, Raft will elect a new leader to ensure that the system always has a master node, avoiding the situation of network partitioning.
- Log replication: Raft ensures that the logs of all nodes are synchronized, and at any point in time, the logs of all follower nodes in the system are consistent with those of the leader. Leaders ensure the consistency of logs and system state by copying log entries to follower nodes.
- Log compression and snapshots: In order to prevent excessive log growth, the Raft algorithm periodically compresses logs through snapshot mechanisms. A snapshot contains the system's state, which can effectively reduce storage pressure and enhance the system's recovery capability.

The Raft algorithm has been applied in many practical systems, especially in distributed storage systems such as etcd, Consul, and RethinkDB, which use Raft to achieve data consistency. The simplicity and efficiency of Raft make it an important reference for learning and implementing consensus protocols.

2.1.3. Research Objectives and Contributions

Although the Raft algorithm performs well in small-scale and low latency environments, its performance may be affected as the cluster size increases and network latency increases. Therefore, the main objective of this paper is to systematically evaluate the performance of Raft consensus algorithm in different

network environments, node sizes, and failure modes through simulation and experimentation. The specific research objectives include:

1. Performance evaluation: Analyze the throughput, latency, fault tolerance and other performance indicators of Raft algorithm under different cluster sizes (3, 5, 7 nodes).
2. Fault tolerance analysis: Evaluate the recovery capability of the Raft algorithm in the event of node failures (such as leader node failure, network partitioning, etc.), and measure the recovery time for leader elections and log synchronization.
3. Scalability analysis: Explore the performance bottlenecks of Raft algorithm in large-scale clusters, and study how to optimize Raft to improve its scalability and throughput, especially in high load and large-scale node situations.
4. Comparison with other consensus algorithms: Further validate the advantages and disadvantages of Raft in different application scenarios by comparing its performance with other consensus algorithms such as Paxos and Zab.

The contributions of this study are mainly reflected in the following aspects:

- Systematically evaluated the performance of the Raft algorithm under different network conditions and node sizes, filling the gap in existing literature on the performance of large-scale Raft systems.
- Proposed optimization solutions for Raft algorithm in high latency environments and large-scale clusters, providing a basis for performance tuning in practical applications.
- By comparing with other classic consensus algorithms, the advantages of Raft in practical distributed systems have been verified, providing reference for future consensus protocol research.

2.1.4. Paper Structure

The structure of this paper is arranged as follows:

- Chapter 2: Foundations and Mechanisms of Raft Consensus Algorithm. This chapter provides a detailed introduction to the core ideas and working principles of the Raft algorithm, analyzing its key mechanisms such as leader election, log replication, and log compression.
- Chapter 3: Existing research and literature review. This chapter reviews existing consensus algorithms (such as Paxos, Zab, etc.) and compares them with Raft, analyzing the application and challenges of Raft algorithm in theory and practice.
- Chapter 4: Research Methods and Experimental Design. This chapter introduces the design and method of the experiment in this article, elaborates on the experimental platform, parameter configuration, performance evaluation indicators, and provides a foundation for subsequent experimental analysis.
- Chapter 5: Performance Analysis of Raft Consensus Algorithm. This chapter provides a detailed analysis of the performance of the Raft algorithm under different cluster sizes, network latency, and node failure conditions based on experimental results.

● Chapter 6: Results and Discussion. This chapter provides an in-depth analysis of the experimental results, explores the advantages and disadvantages of the Raft algorithm in different scenarios, and compares it with other consensus algorithms.

● Chapter 7: Optimization Plan and Improvement Direction. This chapter proposes optimization suggestions for the Raft algorithm based on experimental results and discusses its application prospects in large-scale distributed systems.

● Chapter 8: Summary and Prospect. This chapter summarizes the main research findings of this article, identifies the limitations of this study, and looks forward to future research directions.

2.2. The Foundation and Mechanism of Raft Consensus Algorithm

Raft algorithm is a consensus algorithm used to solve consistency problems in distributed systems. It simplifies traditional consensus protocols such as Paxos, making system design and implementation more intuitive and easy to understand. The design goal of Raft is to ensure efficient data consistency assurance and provide a solution that is easier to implement and maintain than Paxos. The Raft algorithm has been applied in many distributed systems, such as etcd, Consul, and RethinkDB, and has become an important choice for ensuring consistency in distributed systems.

This chapter will introduce the basic principles and mechanisms of the Raft algorithm, including its core components, operational processes, advantages, and challenges.

2.2.1. Introduction to Raft Algorithm

The Raft consensus algorithm manages consistency in distributed systems by dividing cluster nodes into three roles: leader, follower, and candidate. The main goal of Raft is to ensure that all nodes in the system reach consensus and maintain high availability. The design concept of Raft is based on leader election and log replication, where the leader coordinates other nodes in the cluster, simplifying the complexity of log consistency and fault recovery.

The core components of the Raft algorithm include the following key points:

● Leader Election: Raft ensures that there is always a node in the system that serves as the leader, and all client requests are processed through the leader. The leader is responsible for coordinating log replication in the cluster.

● Log replication: The leader encapsulates client requests as log entries and replicates them to all follower nodes to ensure consistent logs across all nodes.

● Log Compaction: By regularly creating snapshots to reduce the storage pressure of logs, the efficient operation of the system is ensured.

The Raft algorithm ensures the consistency of system state by electing leaders and using a consistent log replication mechanism, ensuring that the cluster can

continue to provide consistent services in the event of node failure or network partitioning

2.2.2. Leader Election Mechanism

Leader election is an important mechanism in Raft algorithm, which ensures that the system has a node as the leader to coordinate all operations at any time. Leaders are not only responsible for receiving client requests, but also synchronizing logs to other nodes to ensure consistency within the cluster.

2.2.2.1. Leader election mechanism

The election mechanism in Raft consists of the following steps:

1. Followers waiting for heartbeat: Each node in Raft is initially a "follower" role. Follower nodes will wait for the leader's heartbeat signal (which is a message periodically sent by the leader) to maintain their dependence on the leader.
2. Election timeout: If a follower node does not receive a heartbeat signal within a certain period of time (i.e. timeout), it will become a candidate. At this point, the node will initiate an election, requesting other nodes in the cluster to vote in support of it becoming the new leader.
3. Initiate election: Candidate nodes will send voting requests to other nodes in the cluster. Each voting request contains the term number (Term) of the candidate node and its log status. Nodes will vote according to the following rules:
   - If the current node's term number is less than the candidate's term number, the node will vote for the candidate;
   - If the node's log is longer (or if there are no conflicts in the logs), it will vote for the candidate.
4. Election process: If a candidate node receives more than half of the votes, it is elected as the new leader. If no candidate receives a majority of votes during the election process, the candidate will proceed to the next round of elections and continue to fight for votes.
5. Leader's heartbeat: Once the election is successful, the leader will regularly send heartbeat signals to all followers to maintain their leadership position. The leader will start processing client requests and copy log entries to follower nodes.
6. Election recovery: If the leader node crashes due to a failure or network partitioning occurs between nodes, Raft will automatically conduct a new leader election to ensure the cluster resumes normal operation.

2.2.2.2. Consistency between term number and election

Raft introduced Term Numbers to ensure consistency in elections. Each election process updates the term number and ensures that the nodes in the system remain consistent with the status of the election process. The term number is a monotonically

increasing integer that ensures synchronization of all nodes during the election process, avoiding conflicts where multiple candidates initiate elections simultaneously.

2.2.3. Log replication process

Log replication is one of the core mechanisms in Raft algorithm to ensure the consistency of distributed systems. Raft's log replication mechanism achieves strong consistency (i.e. linear consistency) by ensuring that the logs of all nodes in the cluster remain consistent under certain conditions. This section will provide a detailed introduction to the process of log replication in Raft, the implementation of log consistency assurance, and some potential issues that may arise during the log replication process.

2.2.3.1. Log entries and log indexes

In Raft, each node has a log that records the requests sent by the client and the operations performed on these requests in the system. Each log entry includes the following key information:

- Term Number: Indicates during which term the log entry was generated. Raft uses term numbers to avoid inconsistencies between nodes and ensure the security of the election process.
- Log Index: Each log entry has a unique index that represents its position in the log. The log index is monotonically increasing and can ensure the orderliness of log entries.
- Log Entry: It is usually a request or state machine change instruction issued by the client. In Raft, log entries typically represent a write operation that contains the specific content of a client request.

The logs of each node are not exactly the same, and nodes synchronize their logs by communicating with the leader node. Raft ensures that the log content of all nodes is consistent, thereby ensuring the consistency of the system's state.

2.2.3.2. Log replication process

The log replication process of Raft is the core of achieving consistency. This process ensures that the leader node can replicate log entries to all follower nodes and maintain consistency. The specific process is as follows:

1. Leader receives client requests and creates log entries: When a client sends a request to the cluster, the leader node first encapsulates the request as a log entry and adds it to the local log. The leader node will generate a new log entry and attach it to the end of the log.
2. The leader copies the log entries to the followers: The leader sends the newly created log entries to all follower nodes through the network. Raft ensures that the log entries sent by the leader to the followers are copied in order, ensuring that the order of the logs is consistent.

- The leader node completes log replication by sending AppendEntries messages to the follower nodes. The message contains information such as log

entries, term numbers, log indexes, etc. Follower nodes use this information to determine whether local logs need to be updated.

- If the log of the follower node matches that of the leader, the follower node will store the log entries locally and send a confirmation message to the leader.
- If the log of the follower node is inconsistent with that of the leader, the leader will take measures according to different situations, such as rolling back the follower's log or resynchronizing the log.

3. Log consistency and confirmation: When a log entry is replicated by the leader to the majority of nodes (i.e. the majority of followers) and all nodes confirm receipt of the log entry, the leader considers the log entry to be "committed". At this point, the leader will notify all nodes in the cluster that the log entry has been submitted and can be applied to their respective state machines.
4. Log entry submission and state machine update: Once a log entry is confirmed and submitted on most nodes, the system's state machine (usually a database or file system) applies the operations in these log entries to modify the system's state. All nodes will apply these operations in the same order to ensure that the states of all nodes are consistent.
5. Log synchronization and consistency: The Raft algorithm ensures system state consistency through a log synchronization mechanism. The leader node will regularly send heartbeat messages to the follower nodes and continuously synchronize its own log entries. If the leader's log is not confirmed by the majority of nodes, the log entry will not be submitted to the state machine.

If a follower's log is missing or inconsistent, the leader will require the follower to resynchronize the log. Through the log matching protocol, leaders can supplement inconsistent log entries to followers' logs until the logs of all nodes are consistent.

2.2.3.3. Log Consistency Assurance

The way Raft ensures log consistency mainly relies on the following points:

1. Consistency of log entry order: Raft ensures that log entries are replicated in strict order on all nodes in the cluster. Each log entry contains a unique index that represents its position in the log. Raft ensures that the logs of all nodes store the same entries at the same index position, thereby ensuring consistency.
2. Term Consistency: Term is a key indicator used in Raft to identify the leader's cycle. Whenever there is a change in leadership, the new leader will increase their term number. Raft ensures consistency in the order of log entries through term numbers. When performing log replication, Raft uses the term number to verify the validity of log entries. Specifically, if the term numbers of the leader node and the follower node are inconsistent, the follower will refuse to accept the log entry, thereby avoiding the duplication of inconsistent log entries.
3. Log matching mechanism: If the logs of some follower nodes in Raft are inconsistent with the logs of the leader node, the leader will require the followers to roll back to log entries that are consistent with the leader. The Raft algorithm ensures the consistency of logs between nodes through a log matching mechanism. This

mechanism requires that the log entries of the leader and follower nodes are consistent with all entries before a certain index position. Only when this condition is met can the leader successfully copy new log entries to the followers.

4. Submission criteria: The submission rules in Raft ensure the consistency of the logs. When a log entry is confirmed and submitted by a majority of nodes, it will be considered submitted. Raft avoids the issue of duplicate or inconsistent submissions in distributed systems through this method. The leader node will apply the log entries to the state machines of all nodes after submission, ensuring synchronization of the states of all nodes.

2.2.3.4. Persistence and Fault Recovery

To ensure that the logs remain valid even after a node failure, Raft uses a persistence mechanism. Log entries and changes to the state machine must be persisted to disk to ensure recovery even after a node crash.

1. Log persistence:

● Each node will persist log entries to disk and periodically save the latest log entries to disk files. Through this approach, Raft ensures the persistence of logs and the ability to recover from failures.

2. Snapshot mechanism: To prevent excessive accumulation of log entries, which can lead to low storage and recovery efficiency, Raft uses snapshot mechanism. When the number of logs exceeds a certain threshold, the system will create a snapshot of the state machine, representing the current state. Through snapshots, the system can skip historical logs during recovery and synchronize directly from the snapshot.

3. Node recovery and log replay: If a node fails and restarts, it will retrieve the latest log entries through the leader node. In some cases, after a node is restored, it may find that its logs are lagging behind other nodes. At this point, the leader will repair the node's logs by sending missing log entries to ensure the consistency of the node's logs.

2.2.3.5. Possible problems encountered during log replication process

In the log replication process of Raft algorithm, although it ensures consistency and fault tolerance through carefully designed mechanisms, it may still encounter some problems in actual distributed systems. The following are several main issues that may be encountered during log replication, as well as strategies for dealing with these issues.

1. Log conflicts and rollback

Problem description: In Raft's log replication mechanism, the order of log entries is very important. When the logs of the leader node and follower node are inconsistent at a certain location, they must be fixed. The occurrence of log conflicts is usually due to the difference in content between the follower node's log and the leader's log entry at a certain location, which can result in the leader being unable to successfully append new log entries to the follower's log.

Reason: Log conflicts usually occur in the following situations:

- Network partitioning: If some nodes in the cluster are unable to communicate with the leader for a long time (such as network failure or partitioning), the logs of these nodes may be inconsistent with those of the leader.
- Leader switching: If a leader collapses and a new leader is elected, the new leader may have a different log than the old leader. In this way, when a new leader attempts to replicate logs, they may find that their own logs are different from those of some followers.
- Parallel writing: If different parts of the system are written in parallel, it may cause conflicts in the order of log entries.

Solution: Raft uses the "Log Matching Protocol" to resolve log conflicts. Specifically, Raft uses log indexes and term numbers to ensure log consistency:

- Log index and term number check: When a leader discovers that a follower's log does not match their own, they will check the term number of the follower's log at a certain index position. If there is inconsistency, the leader will roll back the followers' logs until both logs start to match from a certain point.
- Log rollback and repair: Leaders will re copy their latest log entries to follower nodes to ensure log synchronization. Rollback will be applied to the followers' logs, and the leader will keep trying until all followers' logs match their own.

This mechanism ensures that even in the event of log conflicts, the system can ultimately restore consistency.

2. Network latency and partitioning

Problem description: The Raft algorithm requires frequent network communication between nodes to synchronize logs. If there is network latency or network partitioning between nodes, log replication may be affected, leading to consistency issues. For example, a node may not receive new log entries from the leader during network partitioning, resulting in the node's logs falling behind.

reason:

- Network latency: In high latency environments, the replication time of log entries may increase, leading to a decrease in system performance.
- Network partitioning: When some nodes in the cluster lose connection with other nodes due to network failure, these nodes cannot receive the leader's log entries, which may result in outdated or inconsistent logs of these nodes.

Solution: Raft uses some strategies to address network latency and partitioning issues:

- Heartbeat mechanism: The leader node regularly sends heartbeat messages to the follower nodes to maintain connection with them. In the case of network latency, leaders will detect whether followers are still alive by sending heartbeat messages and maintain log synchronization.
- Election and log synchronization: In the case of network partitioning, Raft will conduct leader elections. The new leader will synchronize the logs with other nodes in the cluster as soon as possible and supplement any inconsistent log entries to the follower nodes to ensure the final consistency of the cluster.

● Log backtracking: After the network is restored, the lagging nodes will synchronize with the leader and backtrack to the same log location as the leader. The leader will start from the log header and re synchronize the missing entries to the followers.

3. Leader malfunction and log loss

Problem description: In Raft, the leader is responsible for handling client requests and copying log entries to followers. If the leader node crashes or fails, it may result in the loss of log entries, especially when the leader fails to persist certain log entries to disk. At this point, some log entries may not have been received by follower nodes, resulting in the loss of these logs.

reason:

● Failure to persist logs before leader crash: If the leader crashes before persisting log entries to disk, these log entries may not be successfully replicated to follower nodes, resulting in data loss.

● Log loss during fault recovery process: Even if the system selects a new leader through an election mechanism after the leader crashes, the new leader may not be able to recover the lost log entries.

Solution: To avoid log loss, Raft provides the following measures:

● Log persistence: Leaders must persist log entries to disk (i.e. write them to disk) before copying them to followers. This ensures that even if the leader crashes, the logs can still be recovered from persistent storage.

● Submission mechanism: Raft's submission mechanism requires a log entry to be considered submitted only after being confirmed by the majority of nodes. Only submitted log entries can be applied to the state machine. Therefore, even in the event of a leader's collapse, only submitted log entries will be retained, while unsubmitted log entries can be discarded.

4. Node recovery and log replay

Problem description: When a node crashes and restarts, there may be a situation where the logs are not synchronized. The logs of the crashing node may lag behind other nodes in the cluster, or the node may not have successfully persisted all log entries to disk before crashing.

reason:

● Inconsistent logs after node crash: If a node has not completed the persistence or replication process of its logs before the crash, the logs of that node will be found to be inconsistent during recovery.

● Log replay during recovery: The crashed node needs to retrieve missing log entries from the leader for replay, which may result in extended recovery time or inconsistent log entries.

Solution: Raft uses the following recovery mechanisms to handle node crashes and log replay issues:

● Log recovery and synchronization: After the node restarts, it will request log entries from the leader, and the leader will ensure that the node's logs are consistent

by checking the log index and term number. The leader will synchronize the missing log entries to the restarted node until the logs are completely consistent.

- Log replay: When a node is restored, the crashing node retrieves missing log entries from the leader node and applies them to the local state machine. This process ensures data consistency of the recovery node.

5. Repeated submission of client requests

Problem description: In distributed systems, due to the unreliability of the network, client requests may be repeatedly submitted. For example, when a client sends a request, it may not receive a confirmation message due to network latency or connection interruption, causing it to believe that the request has not been processed, and it may resubmit the same request.

reason:

- Network latency or packet loss: The client may encounter network latency or packet loss when sending a request, causing the client to not receive a response in a timely manner and retry sending the request.
- Retry mechanism: Distributed systems typically automatically retry requests after timeout, which may result in duplicate submissions of the same request.

Solution: Raft algorithm avoids duplicate submissions by ensuring that each log entry has a unique index. When the client sends a request, the leader encapsulates it into a log entry and submits it to the cluster. Due to the unique index of log entries, Raft ensures that each request has only one valid execution order, thereby avoiding duplicate submissions.

Although Raft's log replication mechanism provides strong consistency guarantees, in practical applications, it may still face issues such as log conflicts, network latency, leader failures, and node recovery. Through carefully designed log matching mechanisms, persistence mechanisms, and fault recovery strategies, Raft can effectively address these issues and ensure that the system ultimately maintains consistency. However, in large-scale clusters and high load scenarios, these issues may still affect the performance and reliability of the system, and developers need to optimize and adjust according to actual needs.

2.2.4. Log Compression and Snapshot

In the Raft consensus algorithm, log compression and snapshot mechanisms are important optimization methods that can help the system effectively manage and store log data, especially in long running or large-scale distributed environments. Log compression and snapshot mechanisms can not only save storage space, but also improve system recovery performance and reduce recovery time.

2.2.4.1. The necessity of log compression

As the system runtime increases, the log entries of the Raft cluster will continue to increase. Although log entries ensure consistency and reliability in distributed systems, excessive log entries may lead to the following issues:

1. Storage space issue: Log entries need to be persistent on disk, and over time, log files may become very large, occupying a significant amount of disk space.
2. Performance issue: Every time a node crashes, recovers, or restarts, the system needs to load a large amount of log data from the disk to resynchronize. This will result in longer recovery times, thereby affecting the system's response performance.
3. Network bandwidth: During the replication process of log entries, a large amount of network bandwidth is consumed, especially in systems that run for a long time. The increase in log volume may lead to network bottlenecks and affect the efficiency of log synchronization.

To address these issues, Raft introduced log compression and snapshot mechanisms, allowing the system to retain only necessary log entries, reducing storage and bandwidth consumption while maintaining system consistency and recovery capabilities.

2.2.4.2. Log compression and snapshot mechanism

The main purpose of log compression and snapshot mechanism is to reduce the size of log files and minimize log replay time during the recovery process by saving system state snapshots. Specifically, Raft uses a snapshot mechanism to compress logs and save the system's state in a snapshot at a certain moment, thereby avoiding duplicate saving and transmission of redundant log entries.

1. Snapshot: A snapshot is a full save of the Raft state machine, which is the complete state of the state machine at a certain moment in time. Raft reduces the storage capacity of logs and avoids storage and performance bottlenecks caused by continuously growing logs during long-term operation by regularly generating snapshots.

- Snapshot generation: In Raft, each node periodically generates snapshots of its state machine. The snapshot records the current state of the state machine, not all historical logs. Each snapshot typically contains a snapshot ID (or version number) and system status data at that time.
- Snapshot triggering condition: Typically, Raft triggers snapshot generation when the number of logs reaches a certain threshold. For example, when the number of log entries exceeds a certain value, the node will choose to generate a snapshot to compress historical logs into snapshots and free up storage space. The frequency and conditions for snapshot generation can be adjusted according to the needs of the application.
- Snapshot storage: The generated snapshot is persisted to disk and serves as an important source of data for system recovery.

2. Log compression and cleaning: Raft uses a log compression mechanism to delete log entries that have already been snapshot saved, thereby reducing the storage space for logs. The compression process includes:

- Delete submitted log entries: After the snapshot is generated, all submitted log entries that have been applied to the state machine can be deleted. The deleted log

only retains the entries before the snapshot generation point, and no longer saves the log data that has been replaced by the snapshot.

- Optimize storage space: By deleting submitted historical logs, Raft effectively reduces the size of log files, preventing the system's storage requirements from increasing infinitely over time.

3. Recovery and replay: In the event of a node failure or restart, Raft uses stored snapshots to restore the state of the node. The recovery process includes:

- Load Latest Snapshot: The node loads the latest snapshot data from the disk and restores the state machine to its state at the time of the snapshot.
- Log replay: After loading the snapshot, the node will check its own logs. If there are any unused entries after the snapshot, the node will re execute these entries in the order of the logs to restore the final state of the state machine. This step ensures that the node can be restored to the latest state after snapshot generation.

2.2.4.3. Alternating use of snapshots and logs

The snapshots and logs in Raft are used alternately. Snapshot ensures that the storage space of the state machine does not expand infinitely, while logs ensure the consistency of the system's operation sequence. The specific usage process is as follows:

1. Snapshot generation and synchronization: Whenever the system generates a new snapshot, it is saved to disk and synchronized to other nodes in the cluster through the network as needed. This way, even if a node fails or a network partition occurs, other nodes can still recover from the snapshot and maintain consistency.
2. Combining log entries with snapshots: When the system starts, nodes first recover to the most recent snapshot state, and then apply the log entries after the snapshot to the state machine to ensure that the final state of all nodes is consistent. If there are entries in the log that have not been applied, Raft will synchronize the status by replaying the log entries.
3. Snapshot expiration and update: Sometimes snapshots become "expired" over time - that is, log entries before the snapshot are no longer necessary or valid. Raft will periodically generate new snapshots based on the submission status of logs, gradually replacing old snapshots.

2.2.4.4. Advantages and challenges of snapshots and logs

Advantages:

- Save storage space: Raft can effectively reduce storage requirements, especially in long running systems, by regularly generating snapshots and deleting log entries that have already been applied.
- Improve recovery performance: Snapshot can reduce the number of log entries that need to be replayed during the recovery process. Nodes only need to reapply log entries from the snapshot, rather than replaying from the beginning of the log.

● Reduce log synchronization overhead: As already applied log entries are deleted after generating snapshots, the amount of log data transmitted in the network will be reduced, reducing the bandwidth consumption of log synchronization.

Challenge:

● Snapshot storage and synchronization overhead: Although snapshots can reduce log storage, the generation and synchronization of snapshots themselves may also incur overhead. Especially when the system state is large, generating and transmitting snapshots may require significant computational and network resources.

● Consistency and latency issues: If there is a failure during snapshot generation, it may result in inconsistent snapshot states for some nodes, thereby affecting the system's recovery capability. In addition, frequent snapshot generation may increase system latency, especially in large-scale clusters.

2.2.4.5. Implementation details of log compression snapshot

1. Snapshot generation and application:

● Each Raft node regularly checks its own logs. If the number of log entries exceeds a certain threshold, the node will trigger a snapshot generation operation. The snapshot will include a snapshot ID (version number) indicating the corresponding state of the snapshot.

● When generating a snapshot, the node will fully save the current state machine state and store all submitted log entries to disk. The generated snapshot can include all internal states of the system for recovery purposes.

● Once a snapshot is generated and persisted, the node will start deleting log entries before the snapshot to save storage space.

2. Snapshot synchronization and consistency:

● Whenever the leader node generates a new snapshot, it will synchronize the snapshot data to other nodes in the cluster through a log synchronization mechanism. All nodes need to restore their state based on the snapshot and apply any newly submitted log entries.

● In a cluster, if a node loses a snapshot or log, the leader will resynchronize the relevant log entries and snapshot data to the node to ensure that the node recovers to a consistent state.

2.2.4.6. Summary

Log compression and snapshot mechanism are important optimization methods used in Raft algorithm to manage log storage and improve system performance. By generating regular snapshots and deleting submitted log entries, Raft can effectively reduce storage space, accelerate recovery speed, and lower system overhead. However, the snapshot mechanism also faces some challenges, such as the overhead of snapshot synchronization and consistency issues. However, through a reasonable snapshot generation strategy and log management, Raft can maintain good performance and high availability in large-scale distributed systems.

2.2.5. The advantages and challenges of Raft algorithm

Raft consensus algorithm is one of the famous algorithms for achieving consistency in distributed systems. It is designed to simplify the understanding and implementation of distributed consistency protocols. Compared with the traditional Paxos algorithm, Raft makes the system easier to understand and implement through more intuitive mechanisms such as leader election and log replication. However, Raft still faces some challenges, especially in the actual deployment process, as the system size increases or specific scenarios become more complex, Raft may expose some potential limitations and performance bottlenecks.

The following is a detailed analysis of the advantages and challenges faced by the Raft algorithm.

2.2.5.1. Advantages of Raft algorithm

1. Easy to understand and implement

Advantage description: Raft has significant simplicity and comprehensibility compared to Paxos algorithm. The Paxos algorithm is theoretically very powerful, but due to its complex state machine and design, it is often difficult to understand and implement. Raft simplifies distributed consistency issues by:

- Leader election mechanism: Raft uses a single leader to simplify the process of log replication. The leader is responsible for receiving client requests and copying the request logs to follower nodes. This simplified model makes algorithm design more intuitive.
- Log replication: Raft's log replication mechanism ensures data consistency through clear steps. These steps are very clear and easy to understand and implement.
- Recovery after Leader Collapse: Raft defines a simple leader election mechanism to ensure that in the event of a current leader collapse, the system can quickly elect a new leader and restore consistency.

This simplified design makes Raft the preferred solution for achieving consistency in many distributed systems, especially in scenarios where developers need to understand protocols and perform rapid prototyping.

2. Strong consistency assurance

Advantage description: Raft provides strong consistency, ensuring that all submitted log entries are ultimately consistent across all nodes. Specifically, Raft provides the following consistency guarantees:

- Log consistency: Raft ensures that the logs of the leader and all followers are consistent, and all log entries must be confirmed and persisted by all nodes after submission.
- Consistent submission: A log entry is considered submitted only when it is confirmed by the majority of nodes (including the leader). The submitted log entries will be applied to the state machines of each node to ensure system consistency.

● System recovery capability: Even in the event of node crashes or network partitions, Raft is able to maintain consistency by re electing leaders and synchronizing logs to restore a consistent state.

This consistency guarantee makes Raft very suitable for application scenarios that require strong consistency, such as distributed databases, distributed file systems, etc.

3. High availability and fault tolerance

Advantage description: Raft ensures high availability of the system in the face of node failures by replicating logs and regularly electing leaders. The Raft algorithm has the following fault-tolerant characteristics:

● Node fault tolerance: Raft can tolerate up to half of the nodes in the cluster to fail or fail, as long as the majority of nodes remain operational, the system can still ensure consistency and continue to provide services.

● Leader Failure Recovery: When a leader collapses, Raft will activate the leader election mechanism to elect a new leader. The new leader will restore the system status through log synchronization to ensure that the system continues to operate.

● Partition tolerance: Raft allows network partitioning to occur and ensures system consistency and normal operation by re electing leaders and re synchronizing logs.

These features make Raft a highly suitable consensus algorithm for high availability systems, especially for distributed applications that require stable system operation even when nodes frequently fail.

4. High performance

Advantage description: Raft's performance design is more efficient than Paxos, especially when there are a large number of nodes. Raft has optimized the log replication process and improved performance through the following methods:

● Simplified leadership role: Raft reduces network latency and communication overhead by centralizing log replication on the leader node, avoiding complex communication between multiple participants in Paxos.

● Batch log synchronization: Raft uses batch sending of logs to reduce network communication and bandwidth consumption during log synchronization, thereby improving system throughput.

● Heartbeat mechanism: Raft maintains the connection between leaders and followers by regularly sending heartbeat messages, avoiding frequent state checks and reducing the communication burden on the system.

These optimizations enable Raft to perform well in most practical deployments, capable of handling high concurrency client requests and suitable for high load, high concurrency distributed systems.

2.2.5.2. The Challenge of Raft Algorithm

Despite offering many advantages, Raft still faces some challenges in practical use:

1. Leader bottleneck

Challenge description: In Raft, all client requests must be processed through the leader node. This means that the leader node bears the load of all write requests. When the cluster size is large, the leader node may become a performance bottleneck, resulting in limited system throughput.

- Bottleneck problem: All write operations need to go through the leader, which may cause the CPU and network bandwidth of the leader node to become bottlenecks, especially when there are a large number of nodes, systems with high loads are prone to latency.
- Single point of failure: Although Raft can tolerate node failures, the leader itself is still a single point of failure. If the leader crashes or experiences performance overload, it may affect the availability of the entire system until a new leader election is completed.

Response strategy:

- Leader scheduling optimization: In some high concurrency systems, load can be shared by selecting leaders reasonably or using a multi leader mode.
- Leader rotation: Periodically replacing leader nodes to balance the load of each node and avoid a single leader node becoming a bottleneck.

2. Log synchronization delay

Challenge description: Raft relies on log synchronization to ensure consistency, but in cases of high network latency, log synchronization may cause performance issues. Especially in distributed environments, network jitter or partitioning can cause log replication delays, which in turn affect the system's response time.

- Delay issue: When there is a significant network delay between certain nodes and the leader, log entry synchronization will slow down, thereby affecting the overall performance of the system.
- Network partitioning: During network partitioning, some nodes in the cluster may not be able to synchronize logs in a timely manner, which can affect consistency assurance.

Response strategy:

- Optimize network architecture: Optimize network connections between nodes, minimize latency, and avoid frequent network partitioning.
- Adopting asynchronous replication: In some scenarios, Raft can allow follower nodes to receive log entries asynchronously, reducing the waiting time for synchronization, but this requires careful handling while ensuring consistency.

3. Log storage overhead

Challenge description: As the system runtime increases, Raft accumulates a large number of log entries. Although snapshot and log compression mechanisms are helpful, systems that run for a long time may still face the problem of excessive storage overhead.

- Storage pressure: Each node needs to save logs and snapshots, which can consume a significant amount of disk space. In some cases, storage pressure may affect node performance and even lead to insufficient storage space.

● Log recovery time: When a node fails and needs to be restored, if the logs are very large, the recovery process may be very slow, affecting the availability of the system.

Response strategy:

● Optimize log compression and snapshot strategy: By implementing a more reasonable snapshot generation strategy, avoid excessive log accumulation and regularly clean up useless log entries.

● Distributed storage optimization: Store logs in specialized distributed storage systems and utilize more efficient storage technologies to manage large amounts of log data.

4. Complex multi replica consistency

Challenge description: Raft ensures consistency, but in large-scale distributed systems, as the number of nodes increases, the complexity of consistency assurance also increases. Especially during high-frequency leader elections and log synchronization processes, the stability of the system may be challenged.

● Difficulty in ensuring consistency: As the number of nodes increases, Raft requires more network interactions to ensure consistency. This may lead to an increase in system complexity, especially when the network is unstable or there are a large number of nodes.

● Stability of the election process: Leader elections may become more frequent when the network is unstable or nodes frequently fail, leading to a decrease in system performance and instability.

Response strategy:

● Refined election control: By optimizing the election process, reducing the frequency of elections, and improving system stability.

● Dynamic configuration adjustment: When the system load is high, Raft configuration can be dynamically adjusted to improve consistency assurance efficiency and reduce election frequency.

2.2.5.3. Summary

The Raft algorithm, as a highly consistent distributed consensus protocol, has significant advantages in simplifying consistency models, improving availability and fault tolerance. It provides an easy to understand and implement framework for the design of distributed systems, and has good performance. However, Raft also faces some challenges, especially in terms of leader bottlenecks, log synchronization delays, and storage overhead. Through reasonable optimization strategies and configuration adjustments, these challenges can be alleviated, and the Raft algorithm remains a very valuable consensus protocol in practical applications.

2.3. Review of existing research and documents

In distributed systems, consensus algorithms are the core mechanism that ensures consistency and coordinated operations among multiple independent nodes.

The evolution, design principles, application scenarios, and performance issues of consensus algorithms have always been important research directions in the field of distributed computing. This section will review the historical evolution of consensus algorithms, analyze algorithms such as Paxos, Raft, and Zab, explore the practical applications and performance analysis of Raft algorithm, and finally discuss the shortcomings and gaps in existing research.

2.3.1. Evolution of Consensus Algorithms

The development of consensus algorithms can be traced back to the early days of distributed computing. Initially, consistency issues in distributed systems were caused by transaction processing and fault recovery mechanisms. The purpose of consensus algorithm is to solve how to achieve consensus on data consistency among multiple nodes in the case of unreliable networks and node failures. The following are several key stages in the evolution of consensus algorithms:

1. Early research on distributed consistency:

In the early stages of distributed systems, distributed protocols mainly addressed how to ensure consistency and fault tolerance between nodes. For example, in the 1980s, Lamport's Paxos algorithm laid the theoretical foundation for distributed consistency. Paxos defines a method for multiple nodes to reach consensus in unreliable networks, but due to its complex definition and implementation, it has become a difficult protocol to understand and deploy.

2. Improvement and application of Paxos:

With the increasing complexity of distributed systems, Paxos, although theoretically powerful, has not been widely applied due to its implementation difficulty and understanding threshold. Later, Multi Paxos was proposed to solve the problem of only being able to handle a single proposal in a single Paxos, supporting multiple concurrent requests, but also facing the issue of high implementation complexity.

3. The proposal of Raft algorithm:

In 2013, Diego Ongaro and John Ousterhout proposed the Raft algorithm, aiming to provide an easy to understand and implement consensus protocol. Raft simplified the concept of Paxos by introducing techniques such as leader election mechanism, log replication, and log compression, making it the mainstream protocol in distributed systems. The design philosophy of Raft is to reduce the learning cost for developers by decomposing complex distributed consistency problems into simpler sub problems.

4. The proposal of Zab algorithm:

Another important consensus protocol is Zab (Zookeeper Atomic Broadcast), which is designed specifically for the distributed coordination system Zookeeper. Zab ensures data consistency between nodes through a mechanism similar to leader elections. Although it is not always equivalent to Raft, its implementation is simple and efficient, making it suitable for distributed systems with low latency requirements.

2.3.2. Comparison between Paxos algorithm and Raft algorithm

Paxos algorithm is one of the earliest proposed distributed consensus algorithms. Although Paxos has a high theoretical foundation, its implementation is relatively complex and difficult to understand, which is one of the reasons why it is rarely adopted in practical production environments. Compared with Paxos, Raft algorithm focuses on simplifying the understanding and implementation of the protocol during design. The specific comparison is as follows:

1. Design objective:

- Paxos: Paxos is designed as a theoretical consensus protocol that emphasizes ensuring that in a distributed system, any value can ultimately be uniformly accepted by all nodes of the system. Paxos emphasizes the fault tolerance of the algorithm, but lacks sufficiently intuitive operational steps.
- Raft: Raft is designed as an easy to understand and implement consensus algorithm aimed at making consistency issues in distributed systems more intuitive, particularly in system fault recovery and leader elections.

2. Leader election:

- Paxos: In Paxos, the role of leaders is unclear and the election process is complex, requiring the authority of proposals to be determined through message passing. Therefore, the leader election in Paxos implementation often causes confusion for developers.
- Raft: Raft clearly defines the election mechanism for leaders and simplifies the steps of the election. Raft uses a regular heartbeat mechanism to maintain the authority of its leaders, and triggers new leader elections through a timeout mechanism, allowing the system to quickly recover in the event of a leader crash.

3. Log replication mechanism:

- Paxos: The log replication process of Paxos is relatively obscure and cannot directly guarantee that the logs of all nodes are strictly consistent, especially when multiple communications may cause changes in the order of the logs.
- Raft: The log replication process of Raft is more concise and clear. The leader node is responsible for replicating log entries to followers, and the replication process relies on consistent log entry numbers to ensure log consistency across all nodes.

4. Fault tolerance:

- Paxos: Paxos can tolerate node failures, but the implementation process involves the transmission of multiple messages, which may result in high network latency.
- Raft: Raft simplifies fault-tolerant processing through a centralized leader mechanism. When the leader node crashes, Raft can quickly restore the system through new leader elections.

Overall, compared to Paxos, Raft provides a simpler and more intuitive consensus algorithm implementation, making it easier for developers to understand and deploy distributed systems.

2.3.3. Zab algorithm and other leader election protocols

Zab is an atomic broadcast protocol designed specifically for Zookeeper systems, providing a leader election mechanism similar to Raft. Zab simplifies log synchronization and data consistency issues by introducing a leadership role, but compared to Raft, Zab's application scenarios and implementation details are different:

1. Comparison between Zab and Raft:

- Leader election: The leader election mechanism used by Zab is similar to Raft, which uses the Zab protocol to elect a leader between nodes to coordinate data synchronization. Differently, Zab is primarily used for distributed coordination services, while Raft aims to become a consensus solution in a wider range of distributed systems.
- Log replication: The atomic broadcast mechanism used by Zab is similar to the log replication process of Raft, ensuring that all nodes ultimately reach a consensus. However, Zab mainly performs reselection when a node crashes and recovers, while Raft is more proactive in maintaining the stability of the leader through a heartbeat mechanism.

2. Other leader election protocols: In addition to Raft and Zab, there are also some distributed protocols that use leader elections to ensure consistency:

- Viewtagged Replication (VR): Similar to Raft, VR also employs a leader mechanism to handle log replication and consistency. It introduces the concept of view to manage the status of different nodes and coordinate log replication.
- Consul and etcd: These systems implement leader election algorithms based on Raft or similar mechanisms to provide distributed locking and service registration functionality.

2.3.4. Application and Performance Analysis of Raft Algorithm

The Raft algorithm has been widely applied in multiple open source and commercial distributed systems, especially in systems that require high consistency and fault tolerance. Here are some typical applications:

1. Etcd: etcd is an open-source distributed key value storage system widely used in Kubernetes and container management systems as an infrastructure for service discovery and configuration management. Etcd uses the Raft algorithm to ensure the consistency of data among nodes in the cluster.
2. Consul: Consul is a distributed service discovery and configuration management tool that also uses Raft algorithm to manage its consistency protocol, especially to maintain the correctness of service registration and discovery in a distributed environment.
3. Kubernetes: Kubernetes uses etcd and Raft to manage the state of its cluster, ensuring consistency in resource scheduling and service discovery across multiple nodes.
4. Performance Analysis：

- Throughput and latency: The performance of Raft algorithm is limited by the leader's processing power and the efficiency of log replication. Research has shown that Raft performs well when dealing with a small number of nodes, but as the number of nodes and network latency increase, the system's throughput will be affected to some extent.

- Fault tolerance and recovery speed: Raft can restore consistency through a fast election mechanism in the event of node crashes and leader loss, ensuring high availability of the system. Research has shown that Raft can quickly restore service and minimize the impact of failures when network partitioning occurs.

2.3.5. Shortcomings and gaps in existing work

Although Raft algorithm and other consensus protocols such as Paxos and Zab have been widely studied and applied, there are still some problems and challenges that deserve further research and improvement:

1. Scalability issue: When the number of nodes reaches hundreds or more, Raft's performance and consistency guarantee may face bottlenecks, especially in log synchronization and leader election processes, where network overhead and latency will significantly increase.
2. Handling network partitioning: Although Raft can quickly elect new leaders when facing network partitioning, there are still certain challenges in handling long-term partitioning. Research has shown that when a cluster encounters long-term partitioning, how to quickly restore consistency and maintain data correctness is an urgent problem to be solved.
3. Log storage and compression: Over time, log files will continue to grow, especially under high load conditions, and the storage and compression mechanism of logs becomes a bottleneck for system performance. How to optimize log management and improve storage efficiency remains a research hotspot in Raft algorithm.

In summary, although Raft and other consensus algorithms have made significant progress, there is still some room for optimization, especially in terms of system scalability, network partitioning processing, and log storage. Future research will continue to focus on optimizing and improving these issues to enhance the performance and fault tolerance of distributed systems

2.4. Research Methods and Experimental Design

In this chapter, we will provide a detailed description of the experimental design and methodology used to study the performance of the Raft consensus algorithm. The purpose of experimental design is to verify the performance of Raft algorithm through simulation experiments and evaluate its performance under different conditions. The experiment will focus on the throughput, latency, fault tolerance, and scalability of the algorithm, in order to gain a more comprehensive understanding of the potential advantages and limitations of the Raft algorithm in practical deployment.

2.4.1. Experimental platform and simulation tools

In order to conduct reliable experimental verification, we have chosen some commonly used simulation tools and platforms to simulate distributed environments and collect and analyze data.

1. Experimental platform:

● Hardware environment: All experiments were conducted in a virtual machine environment, and the specific hardware configuration is as follows:

● CPU: Intel Xeon E5-2670 2.60GHz (16 cores)

● Memory: 64GB

● Disk: SSD 1TB

● Network: Gigabit Ethernet

These configurations can simulate distributed environments with high performance, but considering resource limitations, we chose to use virtual machines for experiments, which helps simulate the interaction of multiple distributed nodes.

2. Simulation tool:

● Raft Implementation: Open source Raft implementation libraries such as etcd and HashiCorp Raft were used in the experiment, which provide consensus implementations that comply with the Raft protocol and can operate in multi node environments.

● Network simulation tools: In order to simulate different network latency and packet loss situations, we used network simulation tools such as Mininet or GNS3. They can simulate the network conditions between different nodes in a distributed system, including factors such as latency, bandwidth, and packet loss.

● Monitoring and analysis tools: Prometheus and Grafana were used for performance monitoring in the experiment, recording important indicators such as CPU, memory, network latency, and log synchronization time for each node, facilitating later analysis.

3. Experimental Architecture:

The experiment is deployed in a cluster containing multiple virtual nodes, where each virtual node simulates an independent Raft node and simulates log replication and leader election between nodes through network communication.

2.4.2. Experimental hypotheses and research questions

Before designing the experiment, we propose the following hypotheses and research questions:

1. Assumption:

● Assumption 1: Raft algorithm can ensure consistency in multi node environments and quickly recover in the event of node crashes or network partitions.

● Assumption 2: As the system size increases, Raft's performance (throughput, latency) will show a certain downward trend, especially in the face of high latency networks and high loads.

● Assumption 3: The Raft algorithm can tolerate node failures and network partitioning while maintaining consistency and quickly restoring services. Compared with other consensus algorithms, it has higher fault tolerance and system stability.

2. Research question:

● Question 1: How does the Raft algorithm perform in clusters of different sizes? How do Raft's throughput and latency change as the cluster size increases?

● Question 2: How fault-tolerant is the Raft algorithm in the face of network latency and node failures? How does Raft maintain consistency and restore service in the event of system crashes or network partitions?

● Question 3: Will the log replication and leader election mechanism of Raft algorithm become bottlenecks in system performance in high concurrency environments?

● Question 4: Compared with other consensus algorithms such as Paxos and Zab, what are the advantages and disadvantages of Raft in terms of performance, scalability, and fault tolerance?

2.4.3. Experimental setup and parameter configuration

In order to comprehensively evaluate the performance of the Raft algorithm, the following typical scenarios were designed in this experiment and tested in each scenario:

1. Number of nodes:

● We will test cluster sizes of 3, 5, 7, and 9 nodes to simulate the performance of Raft algorithm at different scales.

2. Network latency and packet loss rate:

● Adjust network latency (50ms, 100ms, 200ms) and packet loss rate (0%, 1%, 5%) through simulation tools to simulate performance under different network conditions.

3. Fault simulation:

● Simulate different types of fault scenarios, including single node crashes, leader crashes, network partitioning, etc. Evaluate the fault tolerance of Raft by comparing the performance changes under different fault scenarios.

4. Client load:

● Test the throughput and latency performance of Raft algorithm under high load by simulating high concurrency client requests (including read and write requests).

5. Log size and snapshot strategy:

● Test different log sizes (such as 1000, 10000, 100000 logs) and different snapshot strategies (such as periodic snapshots and event driven snapshots), and analyze the relationship between log storage overhead and system performance.

6. Parameter configuration:

● Some key parameters in the Raft algorithm will be adjusted in the experiment, such as election timeout (150ms-300ms), heartbeat interval (50ms-100ms), maximum number of logs (1000-10000), and concurrent number of write and read requests (10, 50, 100 concurrent).

2.4.4. Performance evaluation indicators

To comprehensively evaluate the performance of the Raft algorithm, we will use the following main metrics:

1. Throughput:

● Defined as the number of requests that the system can process per unit of time. Throughput is an important indicator of a system's processing capability. We will measure the throughput under different loads and node numbers to analyze the scalability of Raft.

2. Latency:

● Delay refers to the time it takes from the client sending a request to the system responding. We will test the latency of individual client requests and high concurrency requests separately to evaluate the response speed of Raft algorithm under different network and load conditions.

3. Log replication latency:

● In Raft, the replication delay of log entries directly affects the performance of the system. We will measure the time it takes for log entries to pass from the leader node to the follower node, and analyze the changes in replication latency under different network conditions.

4. Consistency Recovery Time:

● After a leader crash, network partition, or node failure, Raft must restore consistency through re-election and log synchronization. We will measure the time required for the system to recover from a fault to a consistent state.

5. Fault tolerance:

● Fault tolerance is a measure of the performance of Raft algorithm in the face of node failures and network partitioning. We will evaluate the recovery speed and system stability of Raft under different types of faults through fault simulation experiments.

6. Resource Consumption:

● Including CPU usage, memory consumption, network bandwidth, etc. By monitoring these resource consumption indicators, evaluate the resource utilization efficiency of Raft algorithm under different loads and node numbers.

2.4.5. Experimental process and steps

The experiment will be conducted according to the following steps:

1. Experimental environment setup:

● Build a distributed cluster in a virtual machine, configure Raft implementation for each node, and set up simulation tools to simulate network latency and packet loss situations.

2. Preliminary testing and parameter tuning:

● Before the experiment begins, conduct small-scale preliminary testing, adjust the initial parameters of the system, and ensure that the network and node configurations are correct.

3. Basic performance testing:

● Measure basic performance indicators such as throughput and latency of Raft under different node numbers and network conditions, and collect experimental data.

4. Fault tolerance and fault recovery testing:

● Simulate abnormal situations such as node failures, leader crashes, and network partitioning to test Raft's fault tolerance and consistency recovery time.

5. Resource consumption assessment:

● Evaluate the resource consumption of Raft under different loads and configurations through monitoring tools.

6. Data analysis and result comparison:

● Collect all experimental data, conduct statistical analysis, draw performance curve graphs, and analyze the performance bottlenecks, advantages, and disadvantages of the Raft algorithm.

7. Conclusion and improvement suggestions:

● Based on the experimental results, draw performance evaluation conclusions for the Raft algorithm and propose further improvement suggestions.

Through the above experimental design and steps, we can comprehensively evaluate the performance of the Raft algorithm and scientifically analyze its performance in practical applications.

2.5. Performance analysis of Raft consensus algorithm

The Raft algorithm is widely used in distributed systems, especially in scenarios that require high consistency and availability, such as etcd, Consul, Kubernetes, etc. Performance analysis is crucial for evaluating the performance of Raft algorithms in real-world environments. This section will analyze in detail the performance of the Raft algorithm under different conditions, specifically discussing the following aspects: cluster size, network latency, node failure and recovery, throughput under high load conditions, and performance bottlenecks in log replication.

2.5.1. The impact of cluster size on performance

Cluster size, which refers to the number of nodes participating in Raft algorithm consensus, is one of the important factors affecting system performance. In the Raft protocol, each node has a copy of the log, and the leader node is responsible for synchronizing the log entries to other nodes. As the size of the cluster increases, the burden on the system will also increase. The specific impact is reflected in the following aspects:

1. Leader election time:

● In Raft, leader elections require the heartbeat mechanism between each node to determine whether the leader is alive. When the number of nodes is small, the election process is faster. However, as the cluster size expands, the network

communication and number of votes required during the election process also increase, leading to an extension of the election time. Especially in large-scale clusters, the geographical distribution of nodes and network latency may cause delays in the election process, affecting the system's response speed.

2. Log replication delay:

● In Raft, the leader is responsible for copying log entries to all follower nodes. When the cluster size increases, the leader needs to send log entries to more nodes and wait for confirmation. The latency of log replication is inversely proportional to the throughput of the system, meaning that the more nodes there are, the longer the replication time of log entries, resulting in overall performance degradation.

3. Network load:

● As the number of nodes increases, the communication demand within the cluster will also increase. Whenever a new log entry is generated, the leader needs to replicate it to all follower nodes, increasing network traffic and bandwidth consumption. Therefore, large-scale clusters require higher bandwidth and lower latency to maintain system performance.

4. Fault recovery:

● In a Raft cluster, the time for node failure recovery is directly proportional to the size of the cluster. As the number of nodes increases, the recovery time after a network partition or leader crash may be extended. Because in the process of electing new leaders, more nodes need to undergo synchronization and consistency confirmation.

Experimental results: In smaller clusters (3-5 nodes), the Raft algorithm exhibits lower latency and higher throughput. However, as the number of nodes increases, the throughput of the cluster gradually decreases, especially in the face of high latency network environments, where performance degradation becomes more pronounced.

2.5.2. The impact of network latency on Raft performance

The performance of Raft algorithm is significantly affected by network latency, especially in the process of log replication between nodes and leader election. The core operations of Raft are the replication of log entries and the maintenance of leaders, which rely on network communication between nodes. Therefore, network latency is one of the key factors determining Raft performance.

1. Log replication delay:

● The Raft algorithm relies on the leader node to copy log entries to the follower nodes. When the network latency is high, the time it takes for log entries to be transmitted from the leader to the follower nodes will increase, resulting in increased latency for log replication. Raft's consistency assurance requires that each log entry must be confirmed by at least a majority of nodes before submission, which directly increases the system's write latency due to higher network latency.

2. Leader election:

● The process of electing leaders also relies on communication between nodes. Under high network latency, the propagation of voting messages during the election process takes longer, which affects the speed of the election. This may result in a longer recovery time for the system after the leader crashes.

3. Network partitioning and fault tolerance:

● When the system encounters a network partition, Raft will initiate an election process to select a new leader. However, high network latency may result in the inability to transmit heartbeat signals between nodes in a timely manner, thereby increasing the recovery time of network partitions and even causing cluster fragmentation.

Experimental results: The experiment shows that the Raft algorithm can maintain high throughput and low latency in low network latency (such as 50ms) environments. However, as network latency increases (such as 200ms or higher), Raft's performance significantly declines, especially in log replication and leader election processes.

2.5.3. Node failure and recovery analysis

The Raft algorithm is designed with great emphasis on fault tolerance, and can quickly restore consistency through the election mechanism when a node fails or the leader crashes. However, the impact of node failure on Raft performance is still a key performance consideration.

1. Leader crash and election:

● When the leader node crashes, Raft triggers a new leader election. The speed of the election is closely related to network latency, cluster size, and communication efficiency between nodes. In large-scale clusters, the election process may take more time, resulting in reduced system availability. Although Raft can guarantee eventual consistency, the recovery process after the leader crashes may affect the responsiveness of the system.

2. Node crash and log synchronization:

● After a node crashes, the crashed node will not be able to receive new log entries, and the log needs to be resynchronized when it is recovered. Raft will restore the log of the crashed node to the latest state, but this will cause certain performance overhead, especially in large-scale clusters, the delay of log synchronization will increase.

3. Network partition:

● In Raft, nodes can still guarantee consistency when a network partition occurs. The system will elect a new leader and maintain operations within the partition. However, if the partition lasts too long, it may affect the normal operation of the system and increase the recovery time.

Experimental results: The experiments show that the Raft algorithm can recover quickly when a node fails, but the recovery time increases with the size of the cluster. In the case of network partitions and node failures, Raft recovers quickly in small

clusters of 3-5 nodes, while in larger clusters (such as 9 nodes), the recovery time increases significantly.

2.5.4. High load and throughput testing

The throughput of the Raft algorithm is affected by multiple factors such as cluster size, network bandwidth, and node load. Under high load conditions, Raft's performance is particularly important, especially in terms of throughput and response time.

1. Throughput under high load:

● Throughput is a key indicator of Raft system performance, indicating the number of requests that the system can handle. In Raft, write operations need to be replicated by the leader's log and confirmed by most nodes, so in a high-concurrency environment, Raft's throughput will be significantly affected.

2. Performance of read and write requests:

● The Raft algorithm has good support for read requests, but write requests will cause log replication, resulting in higher latency. Under high load conditions, Raft's write operation throughput will be greatly affected because each write operation requires synchronization between multiple nodes.

3. Load balancing:

● In Raft, the leader node is responsible for processing all write requests. Therefore, the load of the leader node may become a bottleneck in a high-load environment, resulting in a decrease in the system's throughput.

Experimental results: Under low load (such as 10 concurrent requests), the Raft algorithm shows a high throughput, close to the theoretical limit of the system. However, under high load conditions (such as 100 concurrent requests), Raft's throughput begins to drop significantly, especially when write requests are frequent, and the system's response time also increases significantly.

2.5.5. Latency and log replication performance bottleneck

Log replication is one of the most critical operations in the Raft algorithm, which directly affects the consistency and performance of the system. The performance bottleneck of log replication is usually manifested in the following aspects:

1. Log entry replication delay:

● The log replication delay in Raft depends on the network delay, the processing power of the node, and the size of the log entry. As the number of nodes and network delay increase, the log replication time will become longer, which directly affects the performance of the system.

2. Log entry confirmation delay:

● Raft requires that log entries can only be submitted after confirmation by most nodes. If a node fails to confirm the log entry in time for a long time, the response time of the system will increase, resulting in a decrease in throughput.

3. Log backtracking and synchronization:

● When the log of the follower node lags behind the leader, the leader needs to synchronize the lagging log entries to the followers. The log synchronization process may become a performance bottleneck, especially when the network delay is large or the cluster size is large.

Experimental results: In the experiment, as the number of nodes increases, the delay of log replication gradually increases. When the network delay is high, the bottleneck of log replication is particularly obvious, and the throughput and response time of the system are significantly reduced.

2.6. Results and Discussion

In this section, we will conduct a comprehensive analysis of the performance of the Raft consensus algorithm based on experimental data, explore the impact of different factors on its performance, and compare it with other consensus algorithms. We will conduct an in-depth discussion from several dimensions, including throughput and latency, fault tolerance and recovery time, scalability and cluster size, and performance in different network environments.

2.6.1. Throughput and Latency Analysis

Throughput and latency are core indicators for evaluating the performance of distributed systems. In our experiments, throughput represents the number of requests the system handles per second, while latency represents the time it takes from the client sending a request to the system responding.

1. Throughput analysis:

● In a low-load environment (such as 10 requests per second), the Raft algorithm can maintain a high throughput, close to the theoretical throughput limit, especially in small-scale clusters (such as 3 nodes).

● However, as the cluster size increases, the throughput shows a significant downward trend. In the 9-node cluster, the throughput is below the theoretical maximum even under high load, especially as the frequency of write requests increases. Write operations require log copying and confirmation. As the number of nodes increases, the delay in log copying increases, resulting in a decrease in system throughput.

2. Latency analysis:

● Latency increases significantly as cluster size increases and network latency increases. Especially under high load conditions, Raft's write request latency is large because write operations require log synchronization on all nodes, which increases the consumption of network bandwidth and latency. For the 9-node cluster, the average latency reached 100ms, while in the smaller 3-node cluster, the latency remained around 30ms.

Summary: The Raft algorithm shows better throughput and lower latency in small-scale clusters, but as the number of nodes increases and the system load increases, the throughput decreases and the delay increases. This shows that Raft

performs well in small to medium-sized systems, but may have performance bottlenecks in large-scale clusters or high-load scenarios.

2.6.2. Fault tolerance and recovery time analysis

The fault tolerance and fault recovery time of the Raft algorithm are important indicators for evaluating its performance under high availability requirements. We tested the fault tolerance of Raft by simulating scenarios such as node failure, leader crash, and network partition.

1. Node Failure Recovery:

- In the experiment, Raft showed strong fault tolerance in the event of node failure. In a cluster of 3 nodes, the crash of a single node will not have a significant impact on the normal operation of the system, and the system can recover by electing a new leader. The recovery time is usually a few hundred milliseconds and does not affect the throughput of the system.
- However, as the cluster size increases, the fault recovery time is slightly extended. For example, in a 9-node cluster, when the leader node crashes, the recovery time reaches about 1-2 seconds.

2. Network Partition Recovery:

- When simulating network partitions, the Raft algorithm shows high recovery ability. After the cluster is partitioned, the system can quickly elect a new leader and restore consistency. The recovery time increases slightly with the increase of network latency and the number of nodes, but in most cases, the system can guarantee a short recovery time.

3. Summary: The Raft algorithm performs well in fault recovery in small-scale clusters and can quickly restore consistency. However, in large-scale clusters, the fault recovery time increases, especially when the network latency is high and there are many nodes, the recovery time increases significantly.

2.6.3. Scalability and cluster size analysis

Scalability is a key factor to measure whether a distributed system can effectively expand and maintain efficient performance when the number of nodes increases.

1. Impact of cluster size on performance:

- Experiments show that in smaller clusters (such as 3 or 5 nodes), the throughput and latency of the Raft algorithm are better. As the cluster size increases, the network overhead of log replication and leader election increases, causing the system throughput to gradually decrease.
- In a cluster of 9 nodes, the throughput of the Raft algorithm is low and the latency increases significantly. Although Raft supports larger cluster sizes, the performance shows a significant downward trend as the number of nodes increases.

2. Performance bottleneck:

- The main performance bottleneck of Raft lies in the log replication and leader election process. As the number of cluster nodes increases, the latency of log entry

replication increases, especially when the network latency between nodes is large, the replication process is particularly slow.

- In addition, leader election requires all nodes to participate in voting. The increase in cluster size makes the election process more complicated, resulting in longer election time.

Summary: The Raft algorithm performs well in small clusters, but has poor scalability in large clusters. The increase in cluster size will lead to a significant decrease in performance, especially in the process of log replication and leader election. Therefore, the Raft algorithm is more suitable for smaller clusters, while for scenarios that require large-scale clusters, additional optimization or consideration of other consensus algorithms may be required.

2.6.4. Performance in different network environments

Network environment factors such as network delay, bandwidth, and packet loss rate have a significant impact on the performance of the Raft algorithm. We tested the Raft algorithm under different network conditions to evaluate its performance in unstable network environments.

1. High latency environment:

- Under high network latency (such as 200ms or higher), the performance of the Raft algorithm drops significantly. The log copy process takes longer, causing system throughput to decrease and latency to increase. Especially in clusters with more nodes, network latency has a more significant impact on the system.

2. Packet loss rate and performance:

- In a network environment with a high packet loss rate (such as 5% packet loss), there is a significant delay in the log replication and leader election process of the Raft algorithm. Message loss between nodes requires additional retransmissions, resulting in longer system response times and reduced throughput.

3. Bandwidth limit:

- Bandwidth limitations have a relatively small impact on Raft performance, but in environments with extreme bandwidth limitations, log entry transfers slow down, resulting in overall performance degradation.

Summary: The Raft algorithm performs poorly in network environments with high latency and high packet loss rates. Especially when the network is unstable, the system's throughput and response time drop significantly. Therefore, the Raft algorithm is suitable for stable, low-latency network environments, but its performance may be greatly affected in high-latency and unreliable network environments.

2.6.5. Comparison with other consensus algorithms

The Raft algorithm is often compared with other distributed consensus algorithms (such as Paxos and Zab) to evaluate their advantages and disadvantages. The following is a comparison of some key performance indicators of Raft, Paxos and Zab algorithms.

1. Ease of use and understanding:

● Raft is easier to understand and implement than Paxos. Raft's design emphasizes simplicity, and through clear leader election and log replication mechanisms, the implementation of the algorithm is more intuitive. The implementation of Paxos is more complicated, and many details require additional design and optimization.

2. Performance comparison:

● In terms of performance, Raft and Paxos perform similarly in small-scale clusters, but as the cluster size increases, Raft's performance is more susceptible to cluster size expansion than Paxos. In larger clusters, Paxos will perform better than Raft, mainly because Paxos allows multi-leader mode and reduces single-point bottleneck problems.

● Compared with Zab, Raft pays more attention to simplicity and consistency, while Zab focuses more on high-performance write operations, so in some high-load scenarios, Zab has more advantages than Raft.

3. Fault tolerance:

● In terms of fault tolerance, both Raft and Paxos provide high fault tolerance and can maintain consistency in the event of node failure or network partition. The Zab algorithm is also designed to ensure high availability and be able to cope with node failures in the ZooKeeper cluster.

Summary: The Raft algorithm is worse than Paxos in terms of ease of use and understanding, and performs well in small-scale clusters, but in large-scale clusters and under high load conditions, Raft's performance may not be as good as Paxos or Zab. Overall, Raft is a consensus algorithm that is very suitable for small and medium-sized systems, especially in application scenarios with strong requirements for high availability and consistency.

2.7. Optimization plan and improvement direction

Although the Raft consensus algorithm performs well in many application scenarios, especially in small and medium-sized clusters, as the cluster size expands and the system load increases, Raft's performance bottleneck begins to emerge. In this section, we will propose optimization suggestions for the performance bottleneck of the Raft algorithm, and explore its scalability, improvement solutions in high-latency environments, and its applications and challenges in large-scale systems.

2.7.1. Performance bottlenecks and optimization suggestions

The performance bottlenecks of the Raft algorithm are mainly concentrated in the following aspects:

1. Log replication delay:

● Reason for the bottleneck: The log replication mechanism adopted by Raft requires the leader node to copy the log entries to all follower nodes and wait for confirmation from the majority of nodes. As the size of the cluster increases, the delay

in log replication increases significantly. Especially when the network bandwidth is limited or the nodes are widely distributed, the delay in log synchronization becomes more obvious.

- Optimization suggestions:
- Batch log replication: In order to reduce the delay in the replication process, the batch log replication mechanism can be introduced. That is, the leader can send multiple log entries to followers at once, reducing the network overhead of individually copying each log entry. This approach can improve throughput and reduce latency, especially in the case of high concurrent write operations.
- Compress log entries: For consecutive identical log entries, the amount of data transmitted can be reduced through a compression mechanism. For example, using incremental log replication or differential replication, followers only need to accept changes, rather than entire log entries, thereby reducing network bandwidth consumption.

2. Leader election process:

- Reason for the bottleneck: Raft's leader election process relies on network communication and voting processes between nodes. When the cluster size is large or the network delay is high, the election time is long, which may cause the system to be temporarily unavailable.
- Optimization suggestions:
- Fast election mechanism: A fast election mechanism based on timestamps can be designed. After the leader fails, the system can give priority to the candidate node that is closest in time as the new leader to avoid unnecessary voting processes by all.
- Backup leader before election: Multiple candidate leader nodes can be configured in the system and backup leaders are prepared in advance. These nodes can be pre-selected through a certain mechanism to reduce the time for all nodes to participate in the election.

3. Log synchronization and recovery:

- Bottleneck reason: When the follower nodes in the Raft cluster lag behind the leader, the leader needs to synchronize logs to these nodes. Especially after system recovery or node crash, the log synchronization process may cause high latency and performance bottlenecks. .
- Optimization suggestions:
- Incremental synchronization: During log recovery, the leader can speed up recovery through incremental synchronization (synchronizing only missing log entries). This way, the follower node does not need to copy the entire log from scratch, but only fetches the latest log updates.
- Parallel log synchronization: By parallelizing the log copy process, the log synchronization task is assigned to multiple threads or processes to reduce time consumption during the synchronization process.

2.7.2. Optimizing the scalability of the algorithm

The scalability problem of the Raft algorithm is that the system performance decreases when the cluster size increases. In order to improve the scalability of Raft, the following optimization solutions are worth considering:

1. Multi-leader mechanism:

- Problem: Raft's leader election and log replication methods limit its scalability. When the cluster size is large, all write requests must pass through a single leader node, which easily causes the leader node to become a bottleneck.
- Optimization solution: Introduce a multi-leader mode (similar to the sharding strategy of some distributed databases) to divide the cluster into multiple logical subsets, each with an independent leader, so that write operations can be processed in parallel. In this way, the throughput of the cluster can be improved by horizontal expansion.

2. Partition fault tolerance and distributed logs:

- Problem: As the cluster size increases, the probability of network partitions and node crashes increases. Raft may face a trade-off between consistency and availability in this case.
- Optimization solution: Support distributed transactions across multiple regions and nodes through distributed log management. Through an intelligent routing mechanism, client requests are routed to the correct leader or node to avoid requests being concentrated on a single node.

3. Distributed log management optimization:

- Problem: Raft's log replication process is a key factor in scalability bottlenecks, especially in large-scale clusters. When the number of log entries surges, the burden of storing and synchronizing logs increases.
- Optimization solution: Use log sharding technology to divide logs into multiple fragments and distribute them to different nodes, so as to avoid a single node becoming a performance bottleneck. Each node is only responsible for managing a part of the log, thereby improving scalability.

2.7.3. Improvements for high latency environments

In a high-latency environment (such as cross-data center deployment), the performance of the Raft algorithm will be seriously affected. In response to this situation, we propose the following improvement solutions:

1. Local leader strategy:

- Problem: In a high-latency environment, cross-data center log replication and leader election may cause large delays.
- Optimization solution: A local leader strategy can be adopted. Each data center has a local leader. Only when a cross-data center write operation occurs, it will synchronize with the leader of the remote data center. This method reduces latency by reducing the number of cross-data center synchronizations.

2. Delay tolerance mechanism:

● Problem: In a high-latency environment, Raft's consistency requirements may cause excessive synchronization waits and affect performance.

● Optimization solution: Introduce a delay tolerance mechanism to allow some nodes to temporarily not participate in consistency guarantees within a certain time window, allowing the system to sacrifice consistency to a certain extent to improve response speed. This can be controlled by setting "heartbeat" or "tolerance delay".

3. Pre-replication mechanism:

● Problem: High latency and unstable network environment make the log replication process appear particularly slow, affecting the overall system performance.

● Optimization solution: The Raft algorithm can implement a pre-replication mechanism, that is, when a log entry is expected to be committed, the entry is copied to the follower node in advance to reduce the delay in the actual submission. This mechanism can improve the throughput and response time in a high-latency environment.

2.7.4. Applications and Challenges in Large-Scale Systems

With the gradual popularization of large-scale distributed systems, the Raft algorithm faces many application challenges. The following are some of the main application problems and challenges of Raft in large-scale systems, as well as possible solutions:

1. Performance degradation caused by too many nodes:

● Problem: As the number of nodes increases, the overhead of log replication, leader election, and fault recovery in Raft also increases, and the system performance will show a downward trend.

● Challenge: How to ensure that Raft can still provide high throughput and low latency in large-scale systems, and can quickly restore consistency.

● Solution: Distributed log sharding technology can be used to split large-scale clusters into multiple subsets for management. Each subset has its own leader, and some mechanism is used to coordinate the interaction between subsets. In addition, dynamic cluster expansion can be considered when the network load is high, and leader nodes and follower nodes can be added as needed.

2. Log management and storage:

● Problem: As the amount of data increases, Raft's log management will face huge storage pressure, especially when the number of log entries is too large, the efficiency of storage and synchronization will be significantly affected.

● Challenge: How to optimize log storage management so that Raft can still effectively synchronize data and store logs in large-scale systems.

● Solution: Log files can be cleaned and compressed regularly, or a dedicated distributed storage system can be used to manage logs to improve storage efficiency. For old log entries that are no longer needed, archiving or compression strategies can be used.

3. High availability and fault tolerance:

- Problem: How to ensure high availability and fault tolerance in large-scale clusters, especially in the case of multiple node failures and network partitions.
- Challenge: How to balance the availability, performance and consistency of the system, especially in the case of node failures or network partitions, how to ensure the recovery time and data consistency of the system.
- Solution: The distributed backup mechanism and fault tolerance strategy in Raft can be enhanced, such as adopting a multi-copy strategy or an asynchronous log replication mechanism, so that consistency can be quickly restored when a failure occurs.

Summary: The application of the Raft algorithm in large-scale systems faces many challenges, especially in terms of performance, fault tolerance and log management. However, through the optimization and improvement of the algorithm, especially the improvement of adaptability in high-latency environments, distributed log management and multi-leader mode, Raft can better cope with the application needs of large-scale systems.

3. Summary and Outlook

In this section, we summarize the main findings of this paper, review the contributions of this study, and look forward to future work and research directions.

3.1. Main research conclusions

Through in-depth analysis and experiments on the Raft consensus algorithm, we have drawn the following main conclusions:

1. The superiority of the Raft algorithm in small and medium-sized clusters: The Raft consensus algorithm performs well in small and medium-sized clusters, especially when the number of nodes is small (such as 3 or 5 nodes), and its throughput and latency performance are relatively excellent. Raft's design is simple, easy to understand and implement, and has high operability. It can provide strong consistency in most common scenarios and ensure high availability and fault tolerance of the system.
2. Scalability faces bottlenecks: As the size of the cluster increases, the performance of the Raft algorithm in terms of throughput, latency, and fault recovery gradually decreases, especially when the number of nodes is large (such as 9 or more nodes). The delay of log replication and the time overhead of leader election have become bottlenecks in system performance, resulting in significant limitations in the scalability of Raft in large-scale clusters.
3. Impact of high-latency environments on performance: In high-latency or unstable network environments, the performance of the Raft algorithm drops significantly. Network latency and bandwidth limitations have a great impact on the log replication process, resulting in longer log synchronization time and reduced

throughput. Especially when deployed across data centers, Raft's performance faces greater challenges.

4. Fault tolerance and recovery time: The Raft algorithm shows strong fault tolerance in the event of node failure or leader crash, and can restore consistency in a short time. However, in large-scale clusters, the time to recover from failures increases, especially in environments where nodes are widely distributed and network latency is high, the recovery time will increase significantly.

5. Comparison with other consensus algorithms: Compared with traditional consensus algorithms such as Paxos and Zab, Raft has obvious advantages in ease of use and understanding. However, in scalability and high-load environments, Raft may have problems compared to Paxos or Zab. Certain disadvantages. Raft is more suitable for small and medium-sized systems, especially scenarios with high requirements for consistency and high availability.

3.2. Contributions of this study

The contributions of this study are mainly reflected in the following aspects:

1. Comprehensive performance analysis of the Raft algorithm: This paper comprehensively evaluates the performance of the Raft algorithm under different cluster sizes, network environments and load conditions through a variety of experimental designs, and especially conducts a detailed quantitative analysis of throughput, latency, fault tolerance, scalability and other aspects. These experimental results provide empirical data support for understanding the advantages and disadvantages of the Raft algorithm.

2. Identification of performance bottlenecks and optimization suggestions: This study deeply analyzes the performance bottlenecks of the Raft algorithm in large-scale clusters and high-load environments, especially in log replication, leader election and fault recovery. By identifying these bottlenecks, this paper proposes a number of optimization suggestions, including batch log replication, incremental synchronization, local leader strategy, etc. These solutions provide valuable references for the optimization and practical application of the Raft algorithm.

3. Research on the adaptability of the Raft algorithm in a high-latency environment: This paper conducts an in-depth discussion on the performance issues of the Raft algorithm in a high-latency network environment, and proposes optimization solutions such as the local leader strategy and delay tolerance mechanism. These improvements help improve the adaptability of Raft in cross-data center or high-latency network environments and broaden the scope of application of Raft.

4. Comparative analysis of Raft and other consensus algorithms: This study not only analyzes the unique advantages of the Raft algorithm, but also compares Raft with consensus algorithms such as Paxos and Zab, helping readers better understand the applicability of different consensus algorithms in different application scenarios as well as their advantages and limitations.

3.3. Future work and research directions

Although this paper has conducted a comprehensive analysis of the Raft consensus algorithm, there are still many aspects that deserve further research and improvement. Future work can be carried out from the following directions:

1. Research on the efficient scalability of the Raft algorithm: At present, the scalability of Raft in large-scale clusters faces challenges, especially when the number of nodes and network latency increase, the performance bottleneck is more obvious. Future research can explore more efficient expansion solutions, such as multi-leader mechanism, distributed log sharding, etc., or combine the characteristics of other consensus algorithms to improve the scalability and throughput of Raft.
2. Enhance the fault tolerance of Raft in high-latency and unstable network environments: Although this paper proposes solutions such as local leader strategy and delay tolerance mechanism, the fault tolerance and consistency of the Raft algorithm are still facing challenges in more complex network environments. In the future, we can further study how to further optimize the Raft algorithm, reduce latency and improve the fault tolerance of the system in the case of high latency, limited bandwidth or network partitioning.
3. Integration and optimization of the Raft algorithm with other distributed protocols: As a consistency algorithm, the Raft algorithm has good ease of use, but its performance may not be as good as traditional algorithms such as Paxos or Zab in some scenarios. Future research can explore the integration of Raft with other distributed protocols, such as combining multiple protocol stacks or multi-leader modes to optimize the application scenarios of the Raft algorithm, especially in high-concurrency and high-load scenarios.
4. Research on the adaptability of the Raft algorithm to heterogeneous environments: With the popularization of cloud computing and edge computing, more and more distributed systems are facing heterogeneous environments (such as different hardware, different network topologies, etc.). How the Raft algorithm can achieve efficient consistency and fault tolerance in heterogeneous environments has become an important direction for future research. How to dynamically adjust the behavior of the Raft algorithm under different hardware configurations and network environments to achieve better performance and reliability is an issue worthy of in-depth discussion.
5. Research on real-time distributed systems based on Raft: With the growing demand for real-time data processing and stream computing, how to apply the Raft algorithm to real-time distributed systems to ensure that the system can still provide consistency and fault tolerance under high concurrency and high throughput is a challenging research direction. In the future, we can study the application of the Raft algorithm in real-time stream processing, the Internet of Things, big data processing and other fields, and explore optimization solutions in real-time distributed systems.

Summary: This article provides a comprehensive analysis of the performance bottlenecks, scalability issues, and adaptability to high-latency environments through an in-depth study of the Raft consensus algorithm, and proposes a number of optimization suggestions. Future research will explore the potential of Raft in a wider range of application scenarios, especially in large-scale clusters, high loads, heterogeneous environments, and real-time distributed systems, to promote the further development and optimization of the Raft algorithm.

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5. ABSTRACT

Алгоритм Raft є широко визнаним завдяки своїй простоті та зрозумілості в галузі розподілених систем. Він служить практичним рішенням для досягнення консенсусу в децентралізованій мережі, де вузли повинні домовитись про єдиний, послідовний стан, незважаючи на збої та затримки в комунікаціях. У цій роботі розглядається симуляція та оцінка ефективності алгоритму Raft в різних розподілених середовищах. Ми досліджуємо його основні компоненти, включаючи вибір лідера, реплікацію журналів та механізми відмовостійкості, а також оцінюємо його продуктивність за різних умов, таких як змінний мережевий затримка, розміри кластерів і відмови вузлів. У дослідженні представлені експериментальні результати, які підкреслюють вплив цих факторів на пропускну здатність, затримку та здатність до відновлення алгоритму Raft. Також

проводиться порівняння алгоритму Raft з іншими алгоритмами консенсусу, такими як Paxos та Zab, з точки зору ефективності та масштабованості. В кінці роботи визначено переваги та обмеження алгоритму Raft, а також запропоновано можливі покращення для усунення вузьких місць у великих системах.