Extend Seata Multi-raft cluster mode

OverView

Due to Seata's file mode storing data in local disk and node memory, it cannot guarantee high availability. On one hand, as a quick-start deployment solution, most users choose db mode for initial setup. On the other hand, for production environments, due to its lack of high availability, file mode is no longer used in production environments. Raft mode was introduced to address the situation mentinoned above.

Process of current Raft mode

1. Request Routing and Verification
   Client Request Sent to TC Cluster
   - The `RaftCoordinator.exceptionHandleTemplate` method first checks whether the current node is the Leader.
   - Only the Leader node can process transaction requests. Non-Leader nodes reject requests and return a NotRaftLeader exception.
2. Transaction Initialization
   Leader Node Processes Global Transaction Start Request
   - The Leader node uses the `RaftSessionManager.onBegin` method to handle the global transaction start request.
   - Creates a `GlobalTransactionDTO` and encapsulates it into a `RaftGlobalSessionSyncMsg` synchronization message.
   - Submits the message to the Raft state machine via RaftTaskUtil.createTask.

   Log Replication and Commit
   - The Leader submits the transaction start operation as a log entry to the Raft group.
   - Ensures log replication to a majority of nodes via the Raft protocol.
   - After acknowledgment by most nodes, the Leader commits the transaction and creates a global session.
3. Branch Transaction Registration Phase
   Branch Registration Request
   - An RM sends a branch transaction registration request to the TC.
   - The request is forwarded to the Leader node via the `RaftCoordinator`.

   Branch Transaction Handling

- The Leader node processes branch registration using the `RaftSessionManager.onAddBranch` method.
- Creates a `BranchTransactionDTO` and encapsulates it into a `RaftBranchSessionSyncMsg` synchronization message.
- Submits the message to the Raft state machine for synchronization.

Lock Resource Handling

- Processes lock resources via `RaftLockManager`.
- Lock information is synchronized to all nodes through Raft logs.

4. Transaction Commit/Rollback Phase

   Commit/Rollback Request

   - A TM sends a commit or rollback request to the TC cluster.
   - The request is forwarded to the Leader node.

   State Change Synchronization

   - The Leader processes global transaction state changes via `RaftSessionManager.onStatusChange`.
   - Creates state change messages and synchronizes them to all nodes via Raft logs.

   Branch Transaction Processing

   - Processes commit/rollback for all related branch transactions.
   - Branch state changes are handled via `onBranchStatusChange` and synchronized.

   Lock Release

   - Releases global transaction locks via `RaftLockManager.releaseGlobalSessionLock`.
   - Lock release operations are synchronized to all nodes via Raft.

5. Transaction Completion Phase

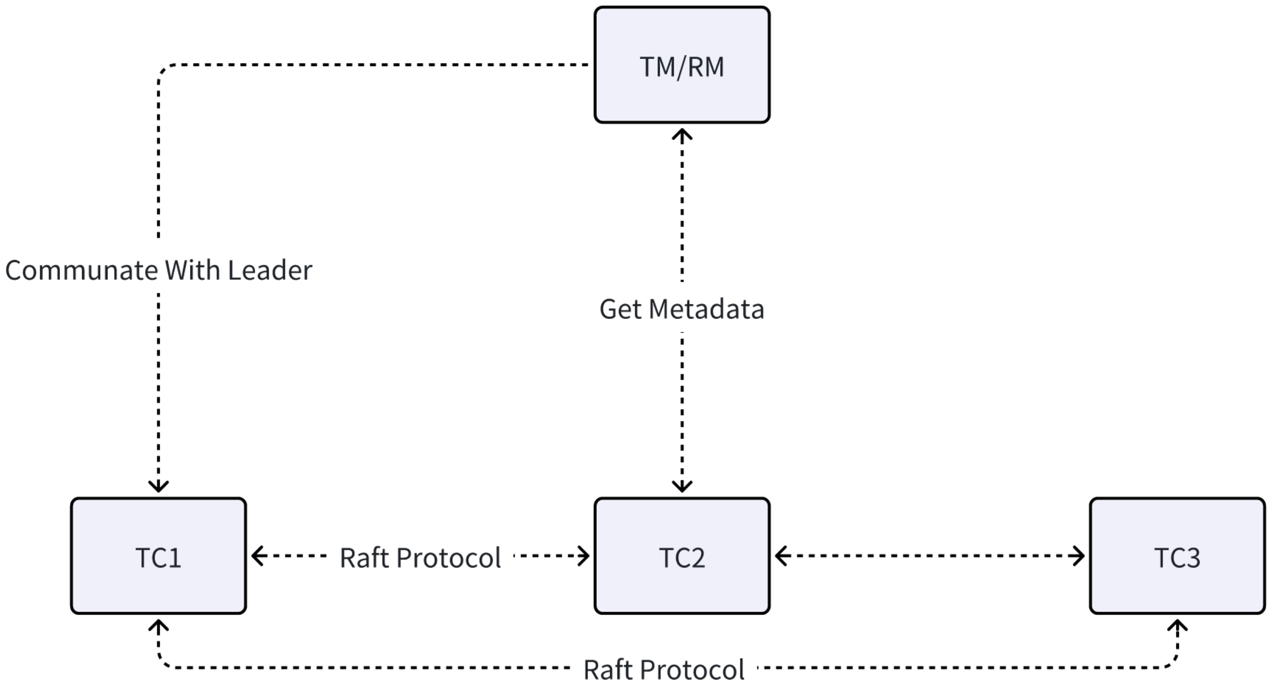
   Transaction Cleanup

   - Successfully completed transactions are cleaned up via `RaftSessionManager.onSuccessEnd`.
   - Failed transactions are handled via `onFailEnd`.
   - Transaction session removal operations are synchronized to all nodes via Raft logs.

Limitation of current Raft mode

1. **Single Raft Group** :The current Raft mode in Seata only supports a single Raft group configuration, which fundamentally constrains horizontal scalability and creates a bottleneck for distributed transaction coordination in large-scale cloud-native environments.

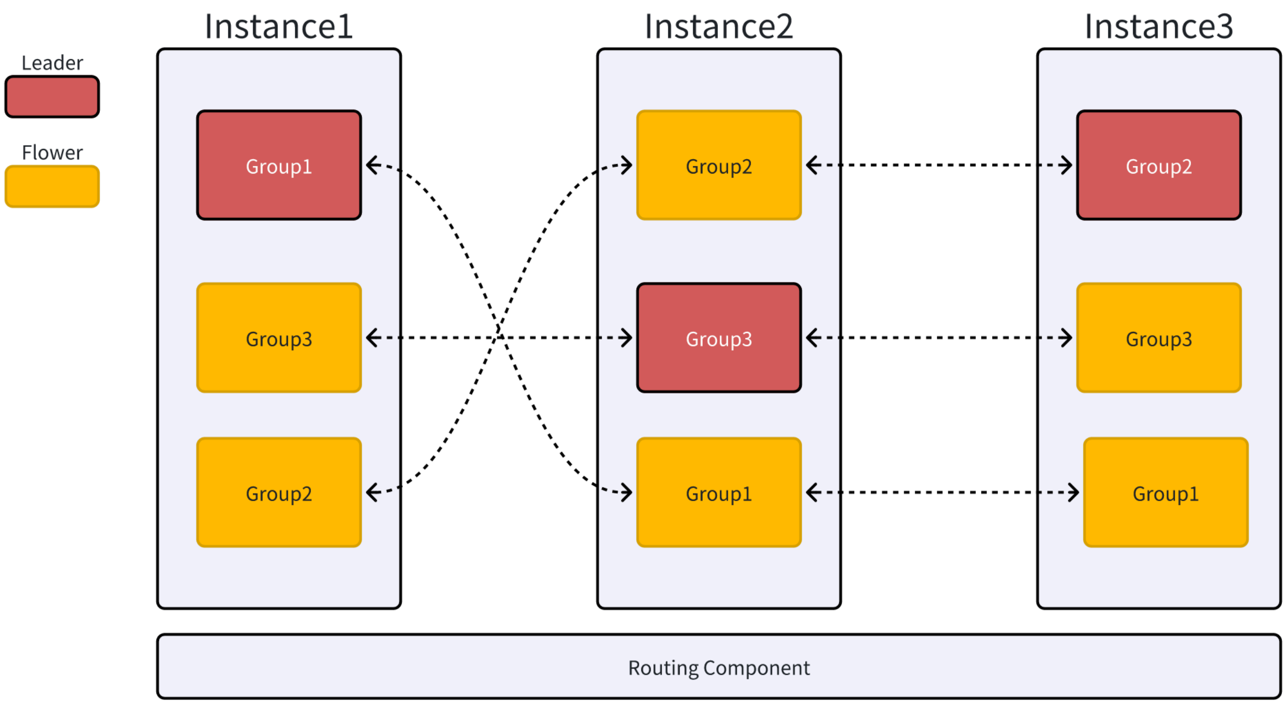
2. **Global Single Point** :All transactional requests must be routed through a single designated Leader node for processing. This centralized processing model creates a performance bottleneck as transaction volume escalates.
3. **Physical Instance Underutilization** :Under heavy workloads, RM/TM components communicate exclusively with the Leader node in the current architecture, while follower instances' computational resources remain untapped.



Multi-Raft Design

Introduce a Multi-Raft architecture to fundamentally enhance horizontal scalability. We could run M Raft Groups on N physical instances(M >= N).This design would:

- **Sharded Transaction Data**: Partition transactions based on predefined rules
- **Virtualized Raft Groups**: Multiple autonomous Raft groups manage distinct shards
- **Role Multiplexing**: Each node serves as Leader for some groups, Follower for others



Key Component Design

1. XID Structure Analysis

   The Seata global transaction ID (XID) follows the standard format:

```
{Ip}:{Port}:{TransactionID}
```

```java
public static String generateXID(long tranId) {
    return new StringBuilder().append(ipAddress).append(IP_PORT_SPLIT_CHAR).append(port).append(IP_PORT_SPLIT_CHAR).append(tranId).toString();
}
```

   - Ip: Ip address of TC server.
   - Port: The port TC server listen on.
   - TransactionID: Unique transaction ID.

   Due to the uniqueness of transaction IDs, we can establish routing strategies for different Raft groups(such as: last number of XID % groupNumber).

   e.g.

```java
public interface ShardingStrategy {
/**
* determine raft group by XID
* @param xid
* @return Raft Group ID
*/
String determineGroup(String xid);

/**
* Get all raft groups
* @return All group Ids
*/
List<String> getAllGroups();
}

// Hash sharding strategy
@LoadLevel(name = "consistent-hash")
public class ConsistentHashShardingStrategy implements  ShardingStrategy {
private final ConsistentHashRouter<String> router;
private final List<String> allGroups;

public ConsistentHashShardingStrategy(List<String> groups) {
    this.allGroups = groups;
    this.router = new ConsistentHashRouter<>(groups, 256);
}

@Override
public String determineGroup(String xid) {
    return router.getNode(xid);
}

@Override
public List<String> getAllGroups() {
    return allGroups;
}
}
```

2. Multiple Raft Server Management

   This component extends the existing RaftServerManager to support multiple Raft groups operating concurrently. It provides centralized management for all Raft groups running across physical nodes.

Key responsibilities include:

- Initializing multiple Raft groups with their individual configurations
- Managing the lifecycle of each Raft server instance
- Providing group-specific status information (leader status, term number)
- Facilitating inter-group communication and coordination
- Maintaining a global view of all operational groups

3. Enhanced File Registry Integration

   Since Seata's Raft mode currently only supports the file registry center, we enhance this integration to work effectively with multiple Raft groups:

   - Extended File Structure: The file registry is extended to store group-specific information
   - Group-Aware Configuration: Registry entries include group identifiers for routing
   - Leadership Records: Each group's leader information is separately maintained

4. Session Manager

   Current `RaftSessionManager` only support managing all sessions of single raft group. The Hybrid Session Manager extends Seata's session management capabilities to work with multiple Raft groups. It maintains separate session contexts for each group while providing a unified interface for transaction management. It is needed to create a mapping from XID to a specific Raft group in order to support multi-Raft.

```java
@Override
public void addGlobalSession(GlobalSession globalSession) throws TransactionException {
    super.addGlobalSession(globalSession);
}
```

   Key features include:

   - Group-specific session managers for isolated transaction state management
   - XID-based routing to appropriate session managers
   - Transaction recovery capabilities across multiple groups
   - Resource locking coordination across groups
   - Efficient state persistence leveraging Raft's replication mechanisms

5. RaftCoordinator

   Current `RaftCoordinator` only support sigle raft group:

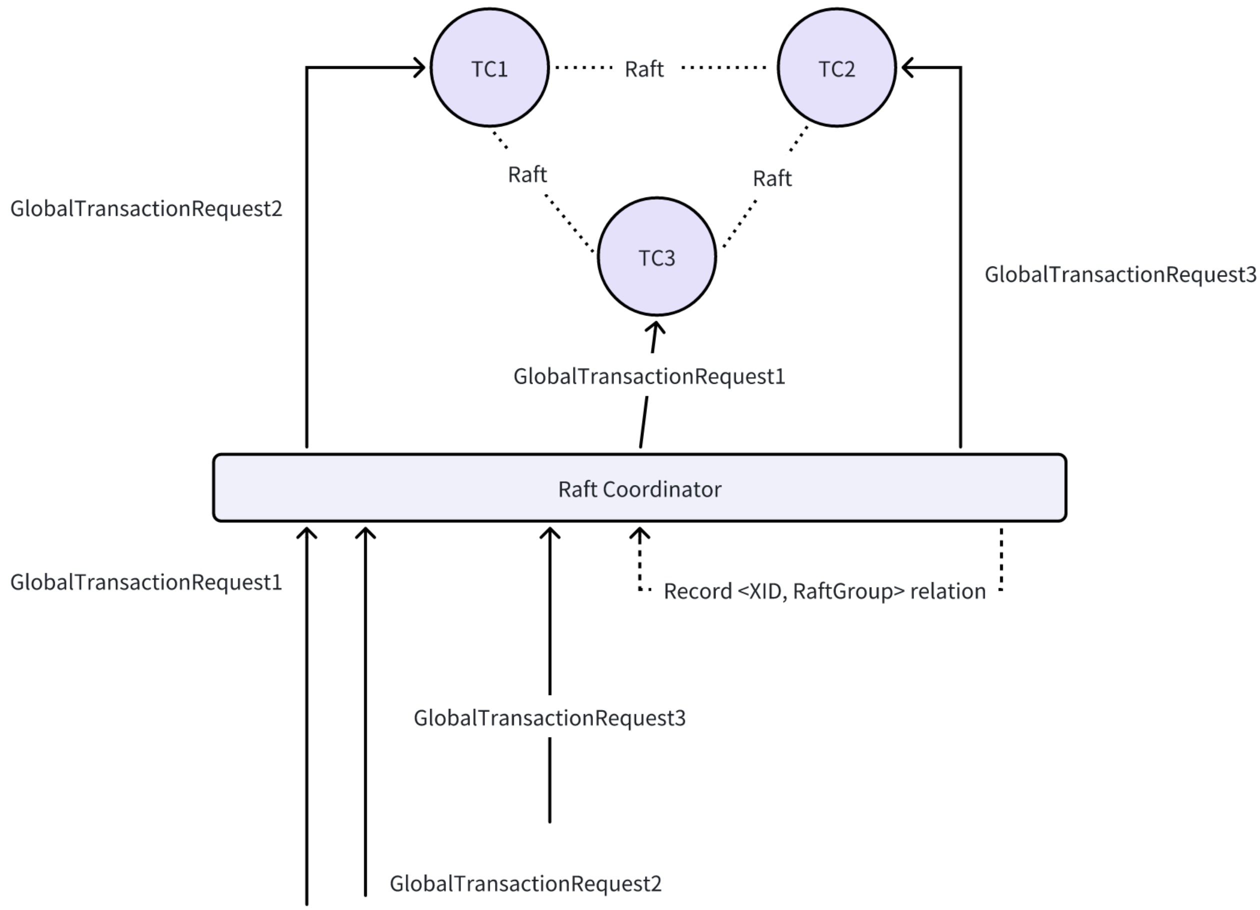
```java
@Override
public <T extends AbstractTransactionRequest, S extends AbstractTransactionResponse> void exceptionHandleTemplate(Callback<T, S> callback, T request, S response)
    String group = SeataClusterContext.bindGroup();
    try {
        if (!isPass(group)) {
            throw new TransactionException(TransactionExceptionCode.NotRaftLeader,
                    message:" The current TC is not a leader node, interrupt processing !");
        }
        super.exceptionHandleTemplate(callback,request,response);
    } catch (TransactionException tex) {
        LOGGER.error(format:"Catch TransactionException while do RPC, request: {}", request, tex);
        callback.onTransactionException(request, response, tex);
    } finally {
        SeataClusterContext.unbindGroup();
    }
}

private boolean isPass(String group) {
    // Non-raft mode always allows requests
    return Optional.ofNullable(GROUP_PREVENT.get(group)).orElse(other:false);
}

public static void setPrevent(String group, boolean prevent) {
    if (StoreConfig.getSessionMode() == StoreConfig.SessionMode.RAFT) {
        GROUP_PREVENT.put(group, prevent);
    }
}


@Override
public void onApplicationEvent(ClusterChangeEvent event) {
    setPrevent(event.getGroup(), event.isLeader());
}
```

We need to do following things:

- Add routing logic to `exceptionHandleTemplate` to support routing different requests to different raft groups based on XID.
- Verify the Leader identity of the target Raft group associated with the request. Function `isPass` should be modified.
- Maintain independent Leader status for each Raft group. `onApplicationEvent` should be able to process multi-group envents.
- Monitor leader change events for all Raft groups.
- Attach target raft-group context to individual requests.

Configuration design

```yaml
seata:
  raft:
    # enable multi-raft mode
    multi-raft-enabled: true

    # sharding strategy
    sharding:
      strategy: default
      group-count: 3

    # common raft config
    snapshot-interval: 600
    apply-batch: 32
    max-append-buffer-size: 262144
    max-replicator-inflight-msgs: 256
    election-timeout-ms: 2000
    serialization: jackson

    # specific group config
    groups:
      group-1:
        data-dir: ${user.home}/seata/data/raft/group-1
        server-addr: 192.168.0.1:7091,192.168.0.2:7091,192.168.0.3:7091

      group-2:
        data-dir: ${user.home}/seata/data/raft/group-2
        server-addr: 192.168.0.1:7092,192.168.0.2:7092,192.168.0.3:7092

      group-3:
        data-dir: ${user.home}/seata/data/raft/group-3
        server-addr: 192.168.0.1:7093,192.168.0.2:7093,192.168.0.3:7093
```



Instance Crash Analysis

Consider the following case: We have 3 physical instances called node1, node2 and node3, and Leader-Follower relation are as follows:

```
group-1: Node1(Leader), Node2(Follower), Node3(Follower)
group-2: Node2(Leader), Node1(Follower), Node3(Follower)
```

First of all, `RaftCoordinator` should check leader status when routing request to TC instance.

In the current architecture, after the Group1-Leader receives a global transaction request, Group1 starts replicating the transaction request information. If the Group1-Leader fails at this stage, the existing mechanism leverages the `onStartFollowing` callback function to update the Group1-Leader information. The Raft protocol guarantees that only nodes with the most up-to-date logs can be elected as the new Leader. Since the newly elected Leader retains all transaction details from its predecessor, the transaction can continue uninterrupted.

Furthermore, subsequent requests for this transaction can also be correctly routed to the new Leader.

For Group2, it can continue operating normally because only a single follower is lost. Even in this scenario, if a leader election is triggered, the remaining nodes can still form a majority quorum to ensure uninterrupted operation.

Summary of Actions for Leader Failover:

- Update Routing Table Synchronization
  - Immediately update the global routing table once the new Leader is elected.
- Request Interception and Redirection
  - Non-Leader nodes intercept incoming requests and redirect them to the valid Leader.
- Client Retry and Metadata Refresh
  - Clients receiving a "Not-Leader" response automatically refresh Leader metadata and retry the request.
- Service Discovery Integration
  - Extend the service discovery mechanism to support Multi-Raft group architecture.
- Periodic Synchronization Checks
  - Regularly validate and synchronize routing information to ensure consistency across nodes.
- Coordinator Integration
  - Seamlessly integrate these mechanisms into the existing RaftCoordinator framework.

We can implement an additional mechanism to prevent concurrent failures of multiple Leaders, ensuring transactional availability.

```java
public void handleNoLeaderAvailable(String group) {
    // 1. try to start new election
    triggerLeaderElection(group);

    // 2. consider re-sharding
    if (isElectionTimeout(group)) {
        // excluding current group, route requests to other available group
        redistributeGroupWorkload(group);

        notifyOperationTeam("No leader available for group " + group);
    }
}

private void redistributeGroupWorkload(String unavailableGroup) {
    // get all available groups
    List<String> healthyGroups = getHealthyGroups();

    if (healthyGroups.isEmpty()) {
        // extreme situation, all groups fail
        enterEmergencyMode();
        return;
    }

    // update routing strategy
    shardingStrategy.temporarilyRedistribute(unavailableGroup, healthyGroups);

    LOGGER.warn("Temporarily redistributed workload from group {} to groups {}",
            unavailableGroup, healthyGroups);
}
```

Fallback Mode

When a new Leader cannot be elected (such as when only one node remains), the system needs to enter degraded mode.

```
private void enterDegradedMode(String group) {
    LOGGER.warn("Entering degraded mode for group: {}", group);

    markGroupAsDegraded(group);

    // degrade
    if (isReadOnlyModeEnabled()) {
        // readonlymode
        enableReadOnlyMode(group);
    } else {
        // reject
        rejectAllRequests(group);
    }

    notifyClientsAboutDegradation(group);
}
```

> Node Rejoining

When a node recovers from a failure, it must rejoin its original Raft group. To satisfy this recovery requirement, the system must persist node-to-group membership mappings to stable storage during the system startup.

```
public void start() throws IOException {
```

We can enhance the `start` method in `RaftServer` to check whether the node is in status of *rejoin*.

The cluster must atomically synchronize metadata with the latest state following any membership change.

Multi-Raft Testing

Following the implementation of the Multi-Raft architecture, comprehensive test suites must be developed to validate:

- Leader election correctness across overlapping groups.
- Membership change isolation between shards.

Cluster Node Configuration

- Node Number: 3 physical instances.
- Raft Group Number: 3 Raft groups, each Raft group is responsible for different transaction partitions.

> Partition Functionality Testing

- Data distribution and routing: Verify transaction is correctly routed to corresponding Raft groups
- Partition rebalancing: Test data migration during dynamic partition addition/removal

> Node Failure Testing

- Single node failure: Randomly shut down one node, verify system continues normally
- Multiple node failures:
  - Shut down one non-leader node in each Raft group
  - Simultaneously shut down leader nodes of multiple Raft groups

> Performance Testing

The key driver for implementing Multi-Raft is to enhance system throughput by fully leveraging compute resources on follower nodes, which remain idle in traditional Raft deployments.

For performance benchmarking, refer to the testing methodology detailed in the link provided below.
Seata-Raft Storage Mode in Depth and Getting Started

Performances metrics:

- Transaction requests per second.
- Request response time.
- Transaction concurrency.

Final Deliverables

1. Refactored `RaftSessionManager` and `RaftCoordinator` to support multi group in single cluster.
2. Seata raft mode using the optimized Multi-Raft mode.
3. Ensure compatibility between previous and current versions.
4. Sufficient test cases.

Time Line

May 4-20

1. Participate in Seata community's communication and familiarize with the code and principles of the raft mode.
2. Research high-performance implementation solutions for Multi-Raft mode.
3. Familiarize with the usage of current raft mode.

May 21-28

1. Contribute the basic work, such as documentation or bug fixes to seata community.

June 1-14

1. Modify current raft group to support multiple raft groups.

June 15-30

1. Modify some data structures in `RaftCoordinator` for future enhancement.
2. Modify globalsession discovery logic in `RaftCoordinator`.

July 1-14

1. Complete logic implementation in `RaftCoordinator`.
2. Write test cases to verify the correctness of the implementation.
3. Deliver mid-term implementation documents.

July 15-31

1. Modify `RaftSessionManager` to support Multi-Raft mode.
2. Modify the interaction logic between `RaftCoordinator` and `RaftSessionManager`.
3. Write documentations for new version of `RaftSessionManager`.

August 1-4

1. Complete the modification of `RaftSessionManager` and `RaftCoordinator`.

August 5-21

1. Complete the testing of Multi-Raft, including:
   - Verify the request routing.
   - Verify the node failure-recovery mechanism.

    - Verify the degraded mode.
    - Performance testing.
    - Verify compatibility for old versions.
2. Fix implementation solutions according to the problems found during testing.
3. Write test reports.
4. Write final implementation document

August 22-28

1. Improve the final project implementation document, including implementation solutions and test reports.
2. Merge code and perform final finishing work according to the issues raised in the review.

Personal Information

Basic Information

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Education Background

XDU, Postgraduate, 2024-2027

Skills

1. Proficient in Java programming language and have participated in multiple large-scale Java projects.
2. Familiar with distributed consensus algorithms.
3. Familiar with SOFAJRaft library.