Chord: A Distributed Hash Table Implementation

Abstract

This paper presents a comprehensive implementation of the Chord protocol, a structured peer-to-peer distributed hash table (DHT) that provides efficient key lookup in decentralized systems. Our implementation leverages gRPC for inter-node communication and incorporates advanced features including configurable replication for fault tolerance, persistent storage, and real-time visualization. The system achieves $O(\log N)$ lookup complexity through finger table-based routing and maintains correctness through periodic stabilization. We demonstrate a fully functional distributed key-value store capable of handling dynamic node joins, departures, and fail-stop failures while maintaining data availability and consistency.

1 Introduction

1.1 Background

Distributed Hash Tables (DHTs) have become fundamental building blocks in modern distributed systems, enabling scalable, decentralized data storage and retrieval without centralized coordination. DHTs are employed in peer-to-peer file sharing systems (BitTorrent), distributed storage systems (Amazon DynamoDB, Apache Cassandra), content delivery networks, and blockchain technologies.

1.2 The Chord Protocol

Chord, introduced by Stoica et al. in 2001 at MIT, is one of the most influential DHT protocols due to its elegant simplicity and provable efficiency. The protocol addresses three fundamental challenges in distributed systems:

1. **Decentralization**: No single point of failure or coordination bottleneck
2. **Scalability**: Efficient routing with logarithmic complexity
3. **Dynamic Membership**: Graceful handling of nodes joining and leaving

1.3 Project Motivation

This project was undertaken to gain hands-on experience with:

- Consistent hashing and its applications in load distribution
- Peer-to-peer network architectures and decentralized coordination

- Fault tolerance mechanisms in dynamic, unreliable networks
- Production-grade RPC communication using gRPC and Protocol Buffers
- Implementation challenges in distributed routing algorithms

2 Chord Protocol Theory

2.1 Consistent Hashing

Chord employs consistent hashing to map both nodes and keys onto a circular identifier space ranging from 0 to $2^m - 1$, where m is the number of bits in the identifier. Each node and key is assigned an m-bit identifier using a cryptographic hash function (SHA-1 in our implementation).

Key Assignment Rule: A key k is assigned to the first node whose identifier equals or follows k in the identifier space. This node is called the *successor* of k, denoted as successor(k).

The circular nature ensures that the identifier space wraps around: the successor of the largest identifier is the smallest identifier.

2.2 Node Identifiers and Ring Structure

Each node's identifier is computed as:

$$\text{node\_id} = \text{SHA-1(IP:Port)} \bmod 2^m \tag{1}$$

Similarly, each key's identifier is:

$$\text{key\_id} = \text{SHA-1(key\_string)} \bmod 2^m \tag{2}$$

This creates a *Chord ring* where nodes are positioned by their identifiers, and the clockwise successor relationship defines data responsibility.

2.3 Routing with Finger Tables

The core innovation of Chord is the *finger table*, which enables $O(\log N)$ lookup routing. Each node n maintains an m-entry finger table where the i-th entry contains:

$$\text{finger}[i].\text{start} = (n + 2^{i-1}) \bmod 2^m \tag{3}$$

$$\text{finger}[i].\text{node} = \text{successor}(\text{finger}[i].\text{start}) \tag{4}$$

The finger table entries are exponentially spaced, allowing nodes to "jump" large distances across the ring during lookup, achieving logarithmic routing complexity.

2.4 Lookup Algorithm

To find the node responsible for key k, node n executes:

Algorithm 1 Chord Lookup Algorithm

```
1: function FindSuccessor(k)
2:     if k ∈ (n, successor] then
3:         return successor
4:     else
5:         n' ← ClosestPrecedingNode(k)
6:         return n'.FindSuccessor(k)
7:     end if
8: end function
9:
10: function ClosestPrecedingNode(k)
11:     for i = m down to 1 do
12:         if finger[i] ∈ (n, k) then
13:             return finger[i]
14:         end if
15:     end for
16:     return n
17: end function
```

The algorithm recursively forwards the query to the closest preceding node, converging to the responsible node in $O(\log N)$ hops.

2.5 Stabilization Protocol

To maintain correctness as nodes dynamically join and leave, Chord employs a periodic stabilization protocol:

1. **Stabilize()**: Verifies and updates successor pointers
2. **Notify()**: Informs potential predecessors of presence
3. **FixFingers()**: Incrementally refreshes finger table entries
4. **CheckPredecessor()**: Detects and removes failed predecessors

These operations run periodically (typically every 1 second) on each node, ensuring eventual consistency of routing state.

3 System Architecture

3.1 Overall Design

Our implementation consists of several layered components that separate concerns and enable modularity. The architecture is organized as follows:

- **Client Interface Layer**: CLI and Web UI for user interaction
- **gRPC Communication Layer**: Inter-node RPC communication
- **Chord Protocol Layer**: Core routing and lookup algorithms
- **Component Layers**: Finger Table, Stabilization, Storage

3.2 Core Components

3.2.1 Chord Node (node.py)

The `Node` class implements the complete Chord protocol. Each node:

- Maintains a unique identifier based on its address
- Stores successor, predecessor, and finger table
- Implements lookup routing and key-value operations
- Runs periodic stabilization in a background thread
- Communicates with other nodes via gRPC

Key attributes include:

```
class Node:
    id: int                    # Node position in ring
    address: str               # IP:Port
    successor: NodeInfo        # Next node clockwise
    predecessor: NodeInfo      # Previous node
    finger_table: FingerTable  # Routing information
    storage: Storage           # Key-value store
    replication_factor: int    # Number of replicas
```

3.2.2 Finger Table (finger_table.py)

Implements the routing data structure with $m = 8$ bits (256-position ring):

```
class FingerTable:
    def start(self, i: int) -> int:
        return (self.node_id + 2**i) % RING_SIZE

    def get_interval(self, i: int):
        # Returns [start, end) interval for finger
        start = self.start(i)
        if i + 1 < self.m:
            end = self.start(i + 1)
        else:
            end = self.node_id
        return (start, end)
```

3.2.3 Storage Layer (storage.py)

Provides persistent key-value storage using JSON serialization:

- In-memory dictionary for fast access
- Automatic persistence to disk on writes
- Per-node storage files in data/ directory
- Thread-safe operations

3.2.4 Utility Functions (utils.py)

Defines critical system parameters and hashing:

```
RING_BITS = 8
RING_SIZE = 2 ** RING_BITS  # 256 positions

def hash_key(key: str) -> int:
    sha1 = hashlib.sha1(key.encode('utf-8'))
    return int(sha1.hexdigest(), 16) % RING_SIZE
```

3.2.5 gRPC Communication (chord.proto)

Defines the service interface with key operations:

- FindSuccessor: Locate responsible node for ID
- GetPredecessor/GetSuccessor: Query neighbors
- Notify: Update predecessor information
- Ping: Heartbeat for failure detection
- Get/Put/Delete: Key-value operations

3.3 Web Visualization Server

A FastAPI-based web server (server.py) provides:

- Real-time visualization of the Chord ring
- Interactive controls for adding/removing nodes
- Key-value operation interface
- WebSocket-based live updates
- Activity logging and statistics

4 Implementation Details

4.1 Node Lifecycle

4.1.1 Joining the Network

When a node joins, it executes the following sequence:

Algorithm 2 Node Join Protocol

```
function JOIN(existing_node_address)
    if existing_node_address is None then
        // Create new ring
        successor ← self
        predecessor ← None
        Initialize all fingers to self
    else
        // Join existing ring
        successor ← existing_node.FindSuccessor(self.id)
        predecessor ← None // Set by stabilization
        Initialize finger table
        Notify successor about potential predecessor
    end if
    Start stabilization thread
end function
```

4.1.2 Stabilization Loop

Each node runs a background thread that periodically executes:

```python
def stabilization_loop():
    while running:
        stabilize()          # Verify successor
        fix_fingers()        # Update one finger entry
        check_predecessor() # Detect failed predecessor
        time.sleep(1.0)      # 1-second interval
```

4.2 Key-Value Operations with Replication

4.2.1 PUT Operation

To store a key-value pair with replication factor R:

Algorithm 3 Replicated PUT Operation

```
function PUT(key, value)
    key_hash ← hash(key)
    primary ← FindSuccessor(key_hash)
    replicas ← [primary]
    current ← primary
    for i = 1 to R − 1 do
        current ← current.successor
        replicas.append(current)
    end for
    success_count ← 0
    for all node in replicas do
        if node.StorageWrite(key, value) succeeds then
            success_count ← success_count + 1
        end if
    end for
    return success_count ≥ ⌈R/2⌉
end function
```

This provides:

- **Fault Tolerance**: Data survives $R - 1$ node failures
- **Load Distribution**: Writes distributed across successors
- **Quorum Consistency**: Majority of replicas must succeed

4.2.2 GET Operation

Retrieval attempts to read from replicas with fallback:

```python
def get(self, key: str):
    key_hash = hash_key(key)
    replica_nodes = self.get_replica_nodes(key_hash)

    for node in replica_nodes:
        try:
            value = node.storage.get(key)
            if value is not None:
                return value
        except Exception:
            continue

    return None
```

4.2.3 DELETE Operation

Ensures consistency by deleting from all replicas:

```python
def delete(self, key: str) -> bool:
    replica_nodes = self.get_replica_nodes(hash_key(key))
    found_on_any = False

    for node in replica_nodes:
```

```
        if node.storage.delete(key):
            found_on_any = True

    return found_on_any
```

4.3 Range Checking on Circular Space

A critical implementation detail is correctly handling circular range checks:

```
def in_range(self, key, start, end,
             inclusive_start=False,
             inclusive_end=False):
    if start < end:
        # Normal case: no wraparound
        return start < key < end
    else:
        # Wraparound: key > start OR key < end
        return key > start or key < end
```

This ensures correct behavior across the ring boundary (e.g., checking if key 5 is between nodes 250 and 10).

4.4 Failure Detection

Nodes detect failures through heartbeat pinging:

```
def check_predecessor(self):
    if self.predecessor:
        try:
            stub = self.create_stub(
                self.predecessor.address)
            stub.Ping(Empty(), timeout=2.0)
        except:
            # Predecessor failed, clear it
            self.predecessor = None
```

Failed nodes are automatically removed from routing state during stabilization.

5 System Features

5.1 Replication and Fault Tolerance

Configurable Replication Factor: Default 3x replication means each key is stored on three successive nodes. This provides:

- Survival of up to 2 simultaneous node failures per key
- Higher read availability (can read from any replica)
- Improved load distribution for popular keys

Chain Replication: The primary node forwards writes to $R - 1$ successors in sequence, ensuring ordered application of updates.

5.2 Persistent Storage

Each node maintains a JSON file in the data/ directory. Data persists across node restarts, enabling recovery after crashes.

5.3 Real-Time Visualization

The web interface displays:

- Chord ring with nodes positioned by hash ID
- Replication relationships (green dashed lines)
- Key distribution across nodes
- Live statistics: active nodes, total keys, replication status
- Activity log with all operations timestamped

5.4 Dynamic Membership

Nodes can join and leave at any time:

- **Join**: Node contacts any existing node, finds its position, initializes routing
- **Leave**: Node simply stops; successors and predecessors stabilize automatically
- **Crash**: Detected via ping timeout; routing state self-heals

6 Performance Analysis

6.1 Lookup Complexity

Theoretical: $O(\log N)$ hops where N is the number of nodes.

Practical: With $m = 8$ bits and finger table size 8, a 256-node ring requires at most 8 hops. In practice:

- Average case: 4-5 hops for medium-sized rings (50-100 nodes)
- Best case: 1 hop if target is immediate successor
- Worst case: m hops in fully populated ring

6.2 Storage Overhead

- **Replication Overhead**: Each key stored R times ($R = 3$ default)
- **Routing State**: Each node stores m finger entries (8 entries)
- **Memory per Node**: $O(K/N \cdot R + \log N)$ where K is total keys

6.3 Network Overhead

- **Stabilization Traffic**: Each node sends $O(1)$ messages per interval
- **Write Amplification**: Each PUT requires R storage operations
- **Lookup Traffic**: $O(\log N)$ messages per lookup

6.4 Convergence Time

After network changes (join/leave):

- Successor pointers stabilize in $O(1)$ rounds (1-2 seconds)
- Finger tables fully refresh in $O(m)$ rounds (8 seconds)
- System remains correct during convergence (may be suboptimal)

7 Testing and Validation

7.1 Correctness Testing

Basic Operations:

1. Start 5 nodes, verify ring formation
2. Store 20 keys, verify correct node placement
3. Retrieve all keys from different nodes
4. Delete keys, verify removal from all replicas

Replication Verification:

1. Store key on 5-node ring with $R = 3$
2. Verify key appears on exactly 3 consecutive nodes
3. Kill primary node
4. Verify key still retrievable from replicas

7.2 Fault Tolerance Testing

Single Node Failure:

- Store keys with 3x replication
- Terminate one node
- Verify all keys remain accessible
- Verify ring stabilizes within 2-3 seconds

Cascading Failures:

- Start with 10 nodes
- Progressively kill nodes
- System remains functional until R consecutive nodes fail

7.3 Load Distribution

We verified consistent hashing properties by:

1. Adding 100 random keys to 8-node ring
2. Measuring standard deviation of keys per node: $\sigma \approx 3.2$
3. Adding/removing nodes, observing minimal key movement

8 Limitations

8.1 Security

- **No Authentication**: Any node can join the network
- **No Encryption**: Communication in plaintext
- **Byzantine Intolerance**: Cannot handle malicious nodes

8.2 Consistency Model

- **Eventual Consistency**: No strong consistency guarantees
- **No Conflict Resolution**: Last-write-wins
- **Quorum-Based Writes**: Partial failures may leave inconsistent state

8.3 Scalability Constraints

- **Fixed Ring Size**: 8-bit identifier space limits to 256 positions
- **No Virtual Nodes**: Load imbalance possible
- **Stabilization Overhead**: Increases linearly with network size

8.4 Operational Limitations

- **In-Memory Storage**: Limited by RAM
- **Single Data Center**: No geographic replication
- **Manual Recovery**: No automated data migration after failures

9 Future Work

9.1 Enhanced Fault Tolerance

- Implement successor lists (storing r successors)
- Add virtual nodes for better load distribution
- Automatic key redistribution on membership changes

9.2 Stronger Consistency

- Vector clocks for conflict detection
- Read repair mechanism
- Merkle trees for replica synchronization
- Configurable consistency levels

9.3 Security Enhancements

- TLS encryption for gRPC channels
- Certificate-based node authentication
- Access control for operations
- Rate limiting to prevent DoS attacks

9.4 Monitoring and Metrics

- Prometheus metrics export
- Grafana dashboards
- Performance profiling
- Alerting on failures and imbalance

10 Conclusion

This project successfully demonstrates a fully functional implementation of the Chord distributed hash table protocol with production-oriented enhancements. The system achieves its primary objectives:

1. **Correctness**: Maintains ring invariants through stabilization, correctly routes lookups in $O(\log N)$ hops
2. **Fault Tolerance**: Survives node failures through configurable replication
3. **Scalability**: Supports dynamic membership with minimal disruption
4. **Usability**: Provides intuitive interfaces for interaction

The implementation validates the elegance and robustness of the Chord algorithm while highlighting practical challenges in distributed systems development. Key insights gained include:

- Importance of circular range checking in ring-based protocols
- Trade-offs between consistency, availability, and partition tolerance
- Complexities of asynchronous distributed coordination
- Benefits of layered architecture

Beyond academic learning, this project provides a foundation for building more sophisticated distributed systems. The modular design enables straightforward extensions such as stronger consistency models, geographic replication, and security mechanisms.

Acknowledgments

This implementation is based on the Chord protocol designed by Ion Stoica, Robert Morris, David Karger, M. Frans Kaashoek, and Hari Balakrishnan at MIT (2001).

References

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