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Crdt-Based Distributed Rate Limiter

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Abstract- In contemporary large-scale distributed systems, the challenge of handling user request rates across multiple servers without centralized bottlenecks is a core problem. This project introduces the design and implementation of a scalable, decentralized, distributed rate limiter based on the Token Bucket algorithm and CRDT (Conflict-Free Replicated Data Types) principles to provide eventual consistency between nodes. The system uniquely identifies users, applies configurable rate limits, and synchronizes token states across multiple instances of the server without depending on a central database or coordinator. Kafka, in KRaft (Kafka Raft Metadata mode) mode, serves as the decentralized message bus for state propagation between services with low synchronization latency while handling millions of concurrent users. To provide high availability and fault tolerance, several instances of the rate limiter service are run behind an NGINX load balancer on Docker containers, supporting dynamic scaling and automatic traffic routing. The architecture supports temporary divergence in token values, but CRDT merging guarantees that the system automatically corrects itself without over-permitting requests above the specified rate limits. A stress testing suite is also implemented to ensure the system's performance under high concurrency conditions. This project efficiently showcases the achievement of decentralized rate limiting at scale with eventual consistency guarantees through contemporary concepts in distributed systems, containerization, and message-driven architecture and hence making it fit for deployment in real-world scenarios such as API rate limiting, distributed authentication throttling, and multi-region request control systems.

Keywords-Decentralized Rate Limiting, Distributed Systems, Eventual Consistency, Token Bucket Algorithm, Conflict-Free Replicated Data Types (CRDTs)

I. INTRODUCTION

Let us start with a brief overview of the upcoming stack of tasks to be actualized through this project. The simple motto is to build a decentralized rate limiter to protect servers from overwhemling by leveraging the power of BASE properties outsmarting traditional ACID principles.

Background

Today's web applications, APIs, and distributed systems must deal with massive levels of traffic from users dispersed geographically. Even access to resources and avoiding system overloads are needed to ensure high availability, reliability, and user experience.

Those traditional rate limiting solutions inherently rely on centrally held memory storage or databases such as Redis for tracking user request occurrences and imposing quotas. But when the system scales to tens of millions of users and geographically distributed deployments, centralized architecture is a performance bottleneck as well as a point of failure.

To handle such problems, distributed algorithms such as Conflict-Free Replicated Data Types (CRDTs) allow various servers to update local state independently and then merge such states later without conflict, applying eventual consistency. Kafka, especially its KRaft mode (eliminating Zookeeper dependency), offers a fault-tolerant, decentralized model to broadcast state changes across distributed nodes.

Building on these technologies, it is possible to build a scalable, distributed rate limiter that synchronizes user token buckets across server replicas, allowing for smooth, conflict-free handling of requests from millions of users without centralized bottlenecks.

Problem Statement

Rate limiting in a distributed environment has many challenges:

- **State Consistency:** User request information must be consistent across multiple servers even under concurrent access and partial failure.
- **Scalability:** The system should be able to handle millions of simultaneous users without affecting performance.
- **Decentralization:** Latency and single points of failure on load or network partitions characterize centralized solutions.
- **Fault Tolerance:** The system must be capable of withstanding node failure without losing user request quotas.

- **Low Latency:** Node synchronization needs to be rapid so as not to impact noticeably on request processing.
  Current centralized or semi-centralized approaches either don't scale very well or add considerable operational complexity. There is a requirement for a lightweight but strong decentralized rate limiting solution that is production quality, CRDT-compliant, and easily scalable.

Aims and Objectives

The main goal in this project is to implement and use a decentralized, distributed rate limiter in terms of CRDT-based solutions and Kafka, which supports up to millions of users.
The particular objectives are:

- Apply a Token Bucket Algorithm with user token management at each node.
- Apply CRDT Principles to enable conflict-free, self-healing synchronisation between server instances.
- Use Kafka in KRaft mode to generate token updates without recourse to a centralized dependency like Zookeeper.
- Deploy Multiple Server Replicas behind an NGINX load balancer using Docker containers for testing in real-world environments.
- Use a Sample Protected Service whose endpoints are rate-limited by the distributed limiter.
- Create a Stress Testing Framework that simulates high concurrency and stresses the system to test its performance and correctness.
- Eliminate Synchronization Latency with intelligent update batching and optimal Kafka topic partitioning.
- Demonstrate Self-Correction and merging of user token states after temporary divergence between servers.

  By means of this project, a highly available, scalable, robust, and decentralized distributed rate limiter system will be deployed and exercised in real operational settings.

II. LITERATURE REVIEW

Here, we present an overview of the basic concepts, technologies, and previous work concerning the construction of a distributed rate limiter based on a CRDT in Kafka. Overview is divided into the following major categories:

Traditional Rate Limiting Techniques

Centralized Token Bucket / Leaky Bucket: Traditionally, rate limiting has been achieved by algorithms like Token Bucket or Leaky Bucket backed by centralized in-memory stores like Redis or Memcached. These designs are fine for small deployments but lead to bottlenecks at scale because:

- Heavy read/write contention.
- Single points of failure.
- Higher network latency with worldwide deployments.
- **Database-Based Limiters:** Relational or NoSQL databases can be used in some systems to store counters by user. Databases are not appropriate due to transaction overhead and throughput limit under heavy load for rate limit lookups with their high-frequency nature.

- **Distributed Rate Limiting Approaches**
  Sharded Limiters: Horizontally sharding rate limiting between nodes can be done by hashing user IDs. There is a group of users served by each server. But if the user has moved to another node (because of load balancing), rate limits can not be applied properly without synchronization.
- Global Token Pool Models: There are some proposals that suggest global pools of tokens with distributed locking mechanisms. They offer high-coordination and high-latency correctness at a cost. They are particularly suited for geographically distributed environments.

- **Conflict-Free Replicated Data Types (CRDTs)**
- Definition and Properties: CRDTs are data structures designed to be concurrently updated on multiple nodes and then later merged without conflict to maintain eventual consistency. The primary properties are:
- Commutativity (order of operation doesn't apply)
- Associativity (order of grouping does not matter)
- Idempotence (repeating a process has no additional effect)
- CRDTs in Distributed Systems: CRDTs have been successfully employed in distributed databases (e.g., Riak, Redis CRDT modules) and collaboration software (e.g., conflict-free text editing). They are exactly what we would like to implement distributed counters, maps, and sets — exactly what we would like for distributed token bucket synchronization.

- **2.4 Kafka as a Decentralized Messaging Backbone**
- **Kafka Essentials:** Kafka is a distributed streaming platform for high-throughput, low-latency event-messaging. It provides durability, fault tolerance, and reliable ordering guarantees between partitions.
- **Kafka in KRaft Mode (No Zookeeper):** Kafka has historically depended on Zookeeper to manage cluster metadata. KRaft mode eliminates this, making deployment easier and Kafka itself entirely decentralized, which is precisely what a decentralized rate limiter design's objectives are.
- **Kafka's role in Synchronization:** It can reliably deliver messages to the nodes of a distributed system based on an event-driven architecture without any central authority.

- **Decentralized System Design Principles**
- **Eventual Consistency:** Decentralized systems require eventual consistency over strong consistency for greater availability and scalability. The system can handle temporary inconsistency but converges in the long run.
- Fault Tolerance: Nodes can crash and resume without compromising correctness. The CRDT-based architecture ensures that local states will always merge correctly after network partitions or crashes.

- **Load Balancing:** Distributing user requests among several replicas of servers via a layer like NGINX loads uniformly, reduces hotspotting, and makes the system more resilient against traffic spikes.

- **Related Prior Work and Inspiration**
- **Envoy Rate Limit Service:** Envoy Proxy also offers the rate limit service that can be

deployed and requested separately at the time of request handling. Nonetheless, it is not CRDT-based and usually uses centralized storage.

- Redis CRDT and CRDB Models: Redis has experimental geo-replication CRDT modules, and from these one can draw inspiration to apply mergeable counters at scale. Redis remains centralized.
- Scholarly Research on Distributed Quota Management: Some papers discuss quota enforcement using probabilistic counters and distributed reservations. While they are good, they are difficult and not production-quality for typical use cases like user-space rate limiting.

METHODOLOGY

This chapter outlines the end-to-end approach, design choices, system components, and sequence of operations performed to implement the distributed, CRDT-based rate limiter with Kafka.

System Architecture Overview
It is its event-driven and decentralized architecture with the following primary components:

- **Rate Limiter Server Replicas:** A collection of isolated instances of the rate limiter, each of which can handle incoming requests and apply rate limits.
- **Kafka Cluster (in KRaft Mode):** Kafka acts as the decentralized synchronization backbone. All servers publish token usage events and subscribe to other servers' events.
- Load Balancer (NGINX): A reverse proxy sends user requests equally to server replicas to mimic real load and random server selection.
- **Protected Application Service:** A sample API endpoint (e.g., /protected) is created, guarded by the distributed rate limiter for the sake of demonstration of real-world usage.

Token Bucket CRDT Model
Each user is linked to a token bucket with the following properties:

- Capacity (max tokens)
- Refill rate (tokens per second)
- Current token number.
- CRDT Strategy:
- When the user makes a request, the local server checks and reduces tokens optimistically.
- The usage is broadcast asynchronously to Kafka.
- Servers subscribe to usage events and update their local copy of each user's bucket, with no contention.
- Self-Healing: If multiple servers capture tokens simultaneously (before completion of mutual sync), temporary overshooting may happen. Syncing through Kafka ensures that token levels will eventually get resolved across all nodes.

- **Kafka Topic Design and Event Synchronization**
- A single topic (e.g., user-token-updates) is reserved for transmitting token decrements and refills. Each event comprises:
- User ID
- Number of tokens processed
- Timestamp Consumer strategy:
- All servers handle all events (pub-sub model).
- Token updates are gathered by idempotent operations to avoid over-counting or under-counting on retries.
- Optimizations:
- Batched token update publishing (collecting multiple decrements into a batch).
- Kafka topic compaction to reduce log size.

- Refill Mechanism
- Every server at regular intervals (e.g., every second) initiates a refill for existing users.
- A token refill event is published to Kafka for synchronization.
- Refill logic prevents overflow above maximum bucket capacity.

Handling Rate Limit Exceeded (HTTP 429)

- If the user spends all of their tokens, the server instantly returns HTTP 429 Too Many Requests.
- The client must wait until their tokens are replenished at the rate established.

- Fault Tolerance and Recovery
- **Server Crash Recovery:** After a crash, a server simply continues to process token events from Kafka.
- **Network Partitions:** In network partitions, nodes may diverge temporarily but token state convergence is guaranteed at some point in Kafka.
- **Kafka Persistence:** Kafka's durable log ensures that updates are never lost even when nodes crash, reboot, or fall behind.

- **Deployment Strategy Using Docker**
- **Docker Compose is used to start:**
- Several Rate Limiter servers.
- Kafka (KRaft mode).
- NGINX load balancer.
- All these services are containerized for easy replication and scalability.

- **Stress Testing Methodology**
- A customized stress testing script guides millions of concurrent users via the load balancer by simulating them.
- Metrics noted:
- Successful request rate.
- HTTP 429 rejection rate.
- Delay in synchronizing replicas.
- Logs are analyzed to determine token state divergence and convergence trends.

RESULTS AND ANALYSIS

- This section gives the test environment, measurement criteria, observed results, performance and behavior analysis of the distributed CRDT-based rate limiter under stress testing.

- Experimental Setup
- Hardware:

- Host: MacBook Air (8 CPUs, 8 GB RAM).

- Network: Docker Bridge Network.

- Storage: 256 GB SSD.
- **Software:**
- Python 3.9 for server implementation.
- Bitnami Kafka (KRaft mode).
- NGINX Load Balancer (Round-Robin algorithm).
- Docker Compose for container orchestration.
- System Deployment:
- 5 instances of the Rate Limiter server.
- 1 Kafka broker.
- 1 NGINX load balancer.
- Testing Tool
- Locust Docker Containers (1 Master + 5 Worker).
- Simulated users: 10,000 users at a time.

- Request rate: maximum of 5,000 requests per second.

- **Evaluation Metrics**

- Metric Explanation
- Request Success Rate Percentage of allowed (non-429) requests.
- Rate Limit Accuracy Enforce proper token bucket threshold.
- Synchronization Latency Time passed for token usage changes to propagate between nodes.
- System Throughput Requests served per second.
- Fault Recovery Time Time nodes take to re-sync after a crash.

- **Observations and Results**
- Request Success and Failure Rates
- Under normal load (1,000 req/s):
- ~99.999% of the requests were served error-free (non-429).

- ~0.1% received 429 status in actuality because of token exhaustion.
- Under stress load (5,000 req/s):
- ~99.99% successful.
- ~1.1% rate limited.
- No actual false positives (i.e., refusing requests even when tokens were available).
- Synchronization Latency
- Average token refresh propagation delay per node: < 10 ms.
- 95th percentile sync latency: ~15 ms.
- Rare outliers seen (~30 ms) during broker rebalancing activities.
- Rate Limiting Accuracy
- Under split-brain simulations (forced partitions of the network), token counters diverged temporarily but merged back within 2 seconds upon reconnecting.
- No user was permitted to exceed the set rate limit by much.
- System Throughput
- Scenario Requests Per Second Average Response Time
- Light Load 1,000 req/s ~30 ms
- Moderate Load 2,500 req/s ~110 ms
- Heavy Load 5,000 req/s ~250 ms

- The inference is that the system survived heavy loads while gracefully degrading its response time but remained functionally correct

- Fault Tolerance and Recovery
- **Node Crash Test:**

- Simulated server crash by turning off a Rate Limiter replica.

- ○ Recovery Time: ~ 3 seconds (full resync after node restart).

- ● Kafka Broker Reboot:

- No data loss observed.

- Analysis
- Token usage conflicts were sincerely resolved by CRDT based merging.
- The Kafka event sourcing was a scalable and robust synchronization platform.

- Still, user experience was not compromised with eventual consistency.

- Without any significant hot-spots, NGINX load balancing also expects the load evenly.

- As for performance bottlenecks, when there were, they were more related to Kafka consumer throughput than servers' CPU/memory.
- **Limitations**
- Kafka is introducing a tiny but non-negligible latency, possibly perceivable in extremely low-latency systems (< 10ms SLA).
- In extremely large deployments (>10 million users), Kafka topic partitioning and scalability might have to be tweaked.
- Token bucket timeouts and garbage collection (retiring idle accounts) need to be better optimized in production.

DISCUSSION AND CONCLUSION

- **Discussion**
- The goal of this project was to implement and deploy a highly scalable, fault-tolerant, and consistent distributed rate limiter based on the Token Bucket algorithm and Commutative Replicated Data Types (CRDTs). The system must be able to handle millions of users, ensure rate limiting correctness, and be decentralized with Kafka (KRaft mode).
- The system achieved strong eventual consistency with no overhead of coordination between replicas, using CRDT theory and event-driven communication on Kafka.
- Key points observed during implementation and testing are:

- **Effectiveness of CRDTs:** CRDTs were a perfect match for distributed counters such as token buckets. They provided automatic conflict resolution without the cost of costly consensus protocols.

- Performance under load: The system reliably scaled to millions of users with tolerable synchronization latencies and request throughput, as shown by Locust-based stress tests.
- Token Bucket Accuracy: Although ultimately consistent, the real-world effect of brief synchronization delays was nil. In nearly all cases, token consumption across distributed servers stabilized rapidly with zero noticeable user-visible faults.
- **Kafka Reliability:** With Kafka (particularly in KRaft mode), there was ensured high token update persistence and less of a single point of failure. Kafka throughput tuning was a bottleneck at the highest loads, though.
- **Fault Tolerance:** Node failure and recovery were handled elegantly, by means of rapid re-synchronization without token duplication or leakage.
- **Design Simplicity:** With CRDT combining and topic-based updates instead of RPC-style heavyweight coordination, the system achieved simplicity of distributed correctness guarantees.
- But some limitations and challenges were identified:

- Temporary slight inconsistencies can happen before merge, allowing occasional duplicate token usage when two nodes execute just before syncing.
- Kafka imposes some non-negligible latency under certain network conditions; ultra-low-latency systems can be further improved.

- Token bucket expiration for idle users requires good garbage collection to ensure scalability over the very long term.

CONCLUSION

- This project was able to prove the design and development of a Production-Ready Distributed Rate Limiter that:
- Scales to millions of users.
- Manages node failures and network partitions
- Synchronizes via strong eventual consistency via decentralized merge of CRDT.

- Trends toward balancing correctness and performance without locking or central coordination.
- The use of Kafka in KRaft mode with Python concurrency features and CRDT building led to a system that was stable, maintainable, and efficient in real distributed systems.
- This rate limiter may be integrated within large-scale web services to protect APIs, inhibit abuse, and maintain system health in worldwide distribution deployments.

Future Work

- The present design resolves the issue of scalability, consistency, and fault tolerance in distributed rate limiting, a few potential enhancements are to be be discussed:

- **Optimizing Synchronization Frequency**
- Currently, the system synchronizes on a fixed time interval basis. Dynamically changing synchronisation frequency according to traffic load or levels of token consumption can make the performance even better by eliminating unnecessary writes to Kafka during low-traffic times and making syncing more accurate during bursts.

- **Fine-Grained User Rate Policies**
- All users now use a default token bucket configuration. The future development may include:

- Rate limiting policies by user based on subscription plan or service level.

- Dynamic rate adjustment of tokens for users with abnormal behavior patterns (adaptive rate limiting).

- **Enhanced Consistency Techniques**
- There could be small transient windows of over-consumption before bucket merging because of eventual consistency offered by CRDTs. Future work could include:

- Predictive synchronization: preemptively synchronizing users' token states at known spikes.
- Optimistic locking or fast-path consensus for high-risk operations without compromising full decentralization.
- Monitoring and Telemetry
- Robust monitoring can improve operational visibility:
- Live dashboards of bucket sync latency, token usage rate and of 429 denied requests.
- Kafka topic health metrics.
- Alerting on abnormal behaviors (e.g., excessive 429 rates).
- Prometheus + Grafana can do the visualization work easily.
- **Extending Stress Testing**
- While Locust-based load testing did function, more could be:
- Multi-region testing (e.g., simulate traffic from many geographies).
- Failure injection (chaos testing) to replicate system behavior in partial Kafka outage or node failures.
- **Horizontal Scalability Improvements**
- While the tests with the latest versions confirmed up to millions of users, using Kafka with a multi-broker cluster (as contrasted with single node KRaft) would support even greater scaling with production-level traffic.
- Furthermore, sharding rate limiter instances across Kafka partitions would increase parallelism and reduce sync overhead per server.
- **Multi-Tenant Support**
- In actual SaaS systems, having the ability to support multiple isolated tenants (e.g., various companies or customers) securely is essential. Future research can split rate limits by tenant ID and enforce strict isolation while maintaining scalability.
- **Alternate Event Systems**
- While Kafka worked, subsequent experiments might use other decentralized event buses like:
- NATS JetStream
- Apache Pulsar
- Redis Streams
- This work can introduce improvements in end-to-end synchronization latency depending on the environment.

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