# Pub-Sub Streams for Viewing Traffic

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## Abstract

Data streams are difficult to make distributed, fault-tolerant and also correct. Our system implements a Kafka-style distributed data stream that uses data replication clusters to handle reads and writes to our system. The data streams guarantee an individual's writes will appear in the order they are sent and that the data is appended to the stream in the order that the cluster receives it. The clusters can survive node failures up to half its size before failing the above guarantees.

## Introduction

We would like to use our proposed system to generate heat maps representing street traffic. A map will be divided into equal-sized quadrants and the location data for each quadrant is stored in a single data stream. The stream where clients will write to will be determined by their coordinates via the server. Clients can read from any data stream as well.

Our implementation of the data stream uses clusters of nodes that each try to replicate the same stream. In each cluster we assign a leader to act as the central communication point that clients read and write to. The leader ensures we have an replication factor of N inside the cluster before returning on writes as well as the order of writes in the entire cluster as received by the leader. Our cluster is designed to handle N-1 node failures, including the leader itself, as well as maintaining functionality with existing clients in the event of server failure.

We assume that all the nodes in our system can be trusted and will not behave adversarially though they can be allowed to fail in the system.

### Terminology

We begin by introducing some terminology relevant to our system.

- **Topic**: A data stream to which a *cluster* is assigned. Our system will designate topics as quadrants on a map.
- **Server**: A singular entity which creates and stores *topics*. Internally, it maps each topic to its *Leader* so *Producers* and *Consumers* can connect to them.
- **Producer**: An entity that may create and write data to a *topic*.
- **Consumer***:* An entity that may read data from a *topic*.

- **Cluster**: A group of one *Leader* and many *Follower* nodes that is responsible for maintaining state and responding to queries pertaining to a *topic*.
    - Leader: A special node that acts as a control point for requests from *Producer* and *Consumer* nodes to the *cluster*.
    - Follower: A generic node that serves to replicate data.
    - N: the minimum number of replications that a cluster must ensure

Note: Topics and clusters are mapped bijectively.

# Implementation

The main design features of our system are the server, client libraries, and most importantly, cluster implementation. Specifically, in our cluster we focus on maintaining data consistency between nodes on client writes and being able to elect a new leader from the cluster in the event of a leader failure.

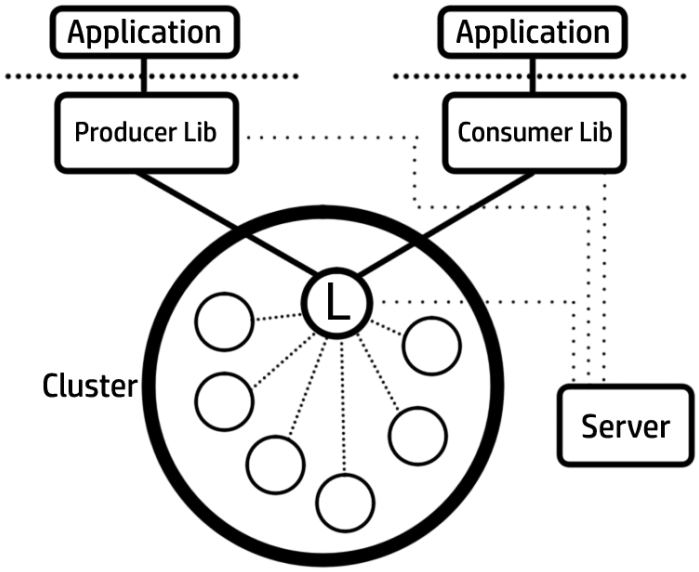


Diagram 1. The basic overview of our system.

## Server

There is a single Server that is aware of all existing topics and which nodes belong to which clusters. The Server provides a Producer node with a cluster (1 Leader + 2*N-1* Followers, where *N* is specified in the server configuration) when it first creates a topic. Topics are assigned per cluster. On startup, the Server will wait for registrations from nodes and establish a heartbeat with them. When nodes fail, the server will also remove them from its active node list.

The only time a Producer should communicate with the Server is when it attempts to create a new topic. When this happens, the server will randomly assign connected nodes that are not yet part of a cluster to the topic the Producer requests. It then sends the list all nodes belonging to the cluster to one of them. A successful return registers that node as the leader of the cluster responsible for the new topic, which is then returned to the Producer who issued the request. If a Consumer wishes to read from a new topic, it must also request the cluster from the Server.

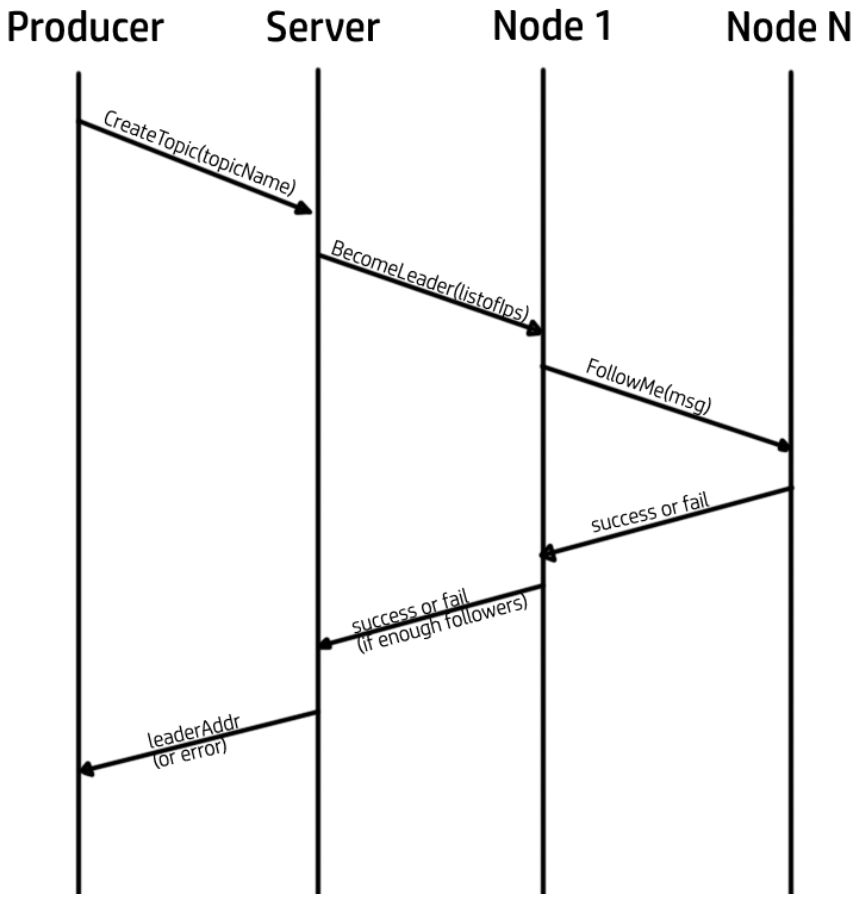


Diagram 2. Creating a new cluster.

The Server can also handle leader replacement on existing topics as a result of new leader election in the event of leader failures.

# Client Libraries

One advantage of our implementation is how easily our client library is built.

The Producer API relies on only 3 calls: `OpenTopic()` and `Write()` or `Close()` to topics. `OpenTopic` returns a session with the cluster leader when successful. A successful `Write` guarantees that the data written will persist in the topic as long as the cluster does not experience a complete failure. However, when the connection to the leader fails during the

write, we do not hide the error from the application and instead allow them to either try to reconnect or otherwise handle the error in their own way. The Consumer API is similar to the Producer API, with the difference being that a Consumer cannot create topics, and the `Write` call gets replaced with a `Read` call which returns the data set from the topic.

# Cluster Operations

The current system implements star topography: the leader has an RPC connection to all the followers, and each follower has an RPC connection to the leader. In order to detect failures, the leader maintains a heartbeat to each follower, and each follower maintains a heartbeat back to the leader. A node failure is detected if either of the following happens: a heartbeat RPC call to a node returns with an error, or a heartbeat from a connected node has not been received for a fixed amount of time (4 seconds at the time of writing).

`Write` calls to the leader update the leader's data set and trigger async calls to all the followers in the cluster. Since we are using async calls, we use a timeout for write confirmations to the Follower nodes. The Leader will block until either 1) there are confirmed writes from N nodes or 2) we receive N+1 timeouts which we consider as failures. The read operation requires no blocking and immediately returns the confirmed writes on the leader's data set.

# Resource Allocation

The number of nodes in a cluster is static during normal operation; this number is set by a server configuration file. Nodes entering our system are initially held by the server without a cluster and are utilized to create a new topic when a Producer needs to create one. Because we hold our clusters in the current star topography we do not want an unnecessary amount of connections to our leader.
The Leader node has a subprocess that monitors the number of followers and compares it to the desired cluster size count. There is a leeway of 1 node to account for nodes temporarily failing but rejoining. When the difference between the follower count and desired cluster size is large enough the subprocess will request that difference from the server and add those new nodes to the cluster.

# Failure Cases

## Server Failure

On server failure any existing clusters and producer/consumer connections will remain intact and not experience any disruptions. However new clients and nodes will not be able to join any new clusters. During a server failure it's possible that a cluster has enough node failures that it ends up failing reads and writes because it can no longer connect to the server and request new nodes.

## Leader Failure and Consensus Protocol

The leader maintains a follower list on each follower on initial connect as well as maintaining the follower list on all nodes in the cluster when nodes join/leave. With this behaviour all nodes in the system are aware of the oldest alive follower in the cluster. The followers are known by an integer ID, with lower integers being the oldest followers. This list can be maintained because a follower is only removed from the list when the leader detects a follower failure. This is a guarantee we make in order to carry out the consensus protocol.

When the leader fails all the follower nodes in the system will detect this through the leader heartbeat. They will then contact the lowest follower IDs in order of their local follower list. Because of the guarantee, we know that nodes reach the same follower who is alive and the oldest alive follower will be on everyone's lists because it could only have been removed if the follower had died. Dead followers on the lists do not matter because the nodes will move on after failing to connect and eventually connect to the oldest alive follower.

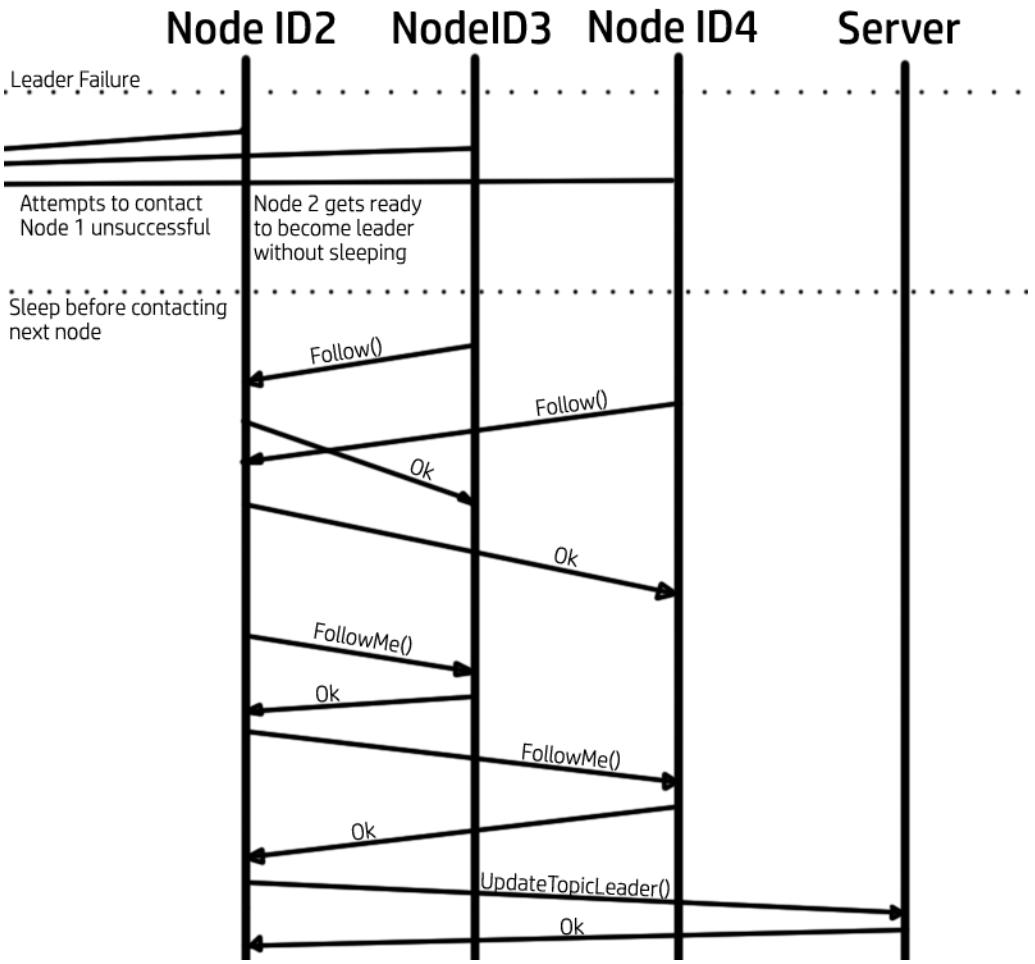


Diagram 3. A leader failure situation with the oldest follower also failing.

When the follower gets enough connects it will switch to leader protocol and commits the follows on all the nodes that connected to it and then call the server to register itself as the new leader of the topic which will allow reads and writes to succeed again. If the follower fails to receive the required number of connections, it assumes that he was passed over (perhaps a network partition) and try to connect to the next follower instead. The format of this protocol resembles 2 phase commit, however the commit-request phase is not decided by the oldest node and instead is decided individually by each node.

Completion of the consensus protocol does not lose any state on the topic though all the follower IDs will be reset under the new leader. A requirement of a node becoming a leader is that it has a complete view of the data. This means when there is a newly elected leader, we must do a data synchronization with other nodes to ensure it has all the data.

### Follower Failure

The leader needs to maintain at least N connections to be considered safe for read/write replication. It always tries to keep 2N-1 nodes in its cluster to keep N as the majority. On follower failure the leader will immediately try to request a new node from the server but is tolerant of up to N-1 failures on the cluster.

### Leader+Follower Failure

If the leader fails and < N nodes fail on the system there are still enough nodes to reach consensus.
In the case where the leader fails and N nodes in the cluster fail in a short timespan we cannot reform the cluster. The to-be-implemented strategy here is a timeout to detect consensus failure. There are two conditions to failing consensus: the node has attempted to become leader and did not get enough followers, and the node never received a “follow me” request. Once the timeout happens, the node tries again on the next entry in it’s follower list until it exhausts the follower list. When this happens the node goes back to the server with it’s data set which will rebuild the (hopefully) complete topic and recreates the cluster.

### Leader+Follower+Server Failure

We can’t do anything about this; this is a catastrophic failure case that we don’t plan to address.

## Challenges

Initially we wanted to increase the performance of our clusters in response to high traffic by delegating additional leaders under high load. However we ran into the issue that we could not maintain a serialized dataset guarantee with this and ultimately had to scrap this idea.

Stability of clusters became an issue because our star topography is very simple and very reliant on the leader. In the future we wish to dedicate a separate workload to designing a specific cluster topography such that followers can connect to other followers and form a chain of command to the leader. Several remaining TODOs in our codebase are related to this extension of the code.

The consensus protocol is not completely foolproof and we can unfortunately reach a failstate in rebuilding the cluster. This is because the timeout period between election and nomination attempts can cause failures, such as nodes attempting to follow a potential leader before it realizes that it needs to ready itself to be leader.

Node rejoins are not perfect because we don't allow nodes to rejoin to the cluster at will. As such the node does store data to disk and retrieve it from disk but that data does not see much use unless the node ends up in the same cluster which is not guaranteed. Our current implementation allows Leaders to request additional nodes from the server when there's more than 1 node failure. We chose this one node failure because

Overall the performance of our prototype could use improvement, but it manages to guarantee a correct serialization of data between multiple clients writing. We plan to make improvements to synchronizing the data during the consensus protocols so that integrity of the data is more likely to survive in the system even after several critical leader failures. We also want to improve our client-side library so that it stores data on drive for offline reads as well as remembers old topic leaders so it can try to circumvent the initial server access.

# Allocation of Work

- **Proposal**: Florie, Jan, Julian, Ruimou
- **Design**: Florie, Ruimou, Jan
- **Cluster Implementation**: Florie, Ruimou
- **Consensus Protocol**: Jan, Ruimou
- **Server Implementation:** Florie
- **Resource Allocation**: Jan
- **Demo Applications & Environment**: Jan, Julian
- **Azure Deployment**: Julian
- **Testing**: Jan, Julian, Florie, Ruimou
- **Report**: Ruimou