Design Document for P2P Publisher-Subscriber System

1. Overview

This document describes the design of a **P2P Publisher-Subscriber System** implemented in Python. The system is based on peer nodes communicating with a central indexing server to create topics, publish messages, and retrieve subscriptions. The primary focus is on simplicity and performance while maintaining scalability and flexibility. This document covers the design decisions, trade-offs, and potential improvements.

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2. Design Approach

The design revolves around the **Central Indexing Server** and **Peer Nodes**. The central server maintains the list of active peer nodes and topics, while the peer nodes manage their own data (topics, subscriptions, messages) locally and coordinate with the server for global management.

Key Design Elements:

- **Indexing Server**: Acts as a central registry, tracking topics, peer nodes, and subscriptions. It provides APIs for peer nodes to register, create topics, subscribe, publish, and query messages.
- **Peer Nodes**: Each peer node is responsible for creating and storing topics locally. Peer nodes interact with the indexing server for registration, topic creation, and messaging. When a peer creates a topic, it hosts the topic on its own storage (following the **Self-Storage Policy**) and registers it with the central server for discoverability.

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3. Self-Storage (Local Creation Policy)

In this system, we use the **Self-Storage** policy where each peer node that creates a topic stores it locally and registers the topic with the central indexing server. This policy is simple but comes with several trade-offs.

How it Works:

- When a peer node creates a new topic, it stores the topic data locally.
- The peer then notifies the indexing server, which updates its topic list to reflect that this peer is the owner of the new topic.
- Messages published to the topic are stored locally by the peer, and other peers can subscribe by querying the central server to discover which peer hosts the topic.

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4. Advantages of the Self-Storage Policy

1. **Simplicity**:
    - The design is straightforward. Each peer node is responsible for its own topics, which simplifies the interaction between peers and reduces complexity.
2. **Low Latency**:

- Since a peer stores and manages its topics locally, publishing and subscribing to messages does not require complex coordination between peers. This reduces latency as the peer can handle requests faster without needing to communicate with other peers.

3. **Local Control**:
    - Each peer node has full control over the topics it creates. This gives the peer node the ability to manage its topics without requiring global coordination.

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5. Trade-offs of the Self-Storage Policy

1. **Load Imbalance**:
    - Since topics are stored locally, popular topics can lead to certain peer nodes being overwhelmed with requests, while other nodes might be underutilized. There is no inherent load-balancing mechanism, which can lead to uneven distribution of resources.
2. **Single Point of Failure**:
    - If a peer node hosting a popular topic goes offline, that topic becomes unavailable unless some form of replication is implemented. This can lead to service disruption for users subscribed to that topic.

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6. Trade-offs in Overall Design

1. **Centralized vs Decentralized Management**:
    - **Centralized Indexing Server**: Provides a simple mechanism to track topics and peer nodes, but it introduces a single point of failure. If the server goes down, peer nodes cannot discover or interact with new topics.
    - **Self-Storage on Peers**: Peer nodes manage their own topics locally, which reduces coordination overhead. However, if a peer hosting a topic goes down, access to that topic is lost.
2. **Performance vs Reliability**:
    - **Performance**: By allowing peer nodes to store and manage topics locally, we reduce the communication overhead. The peer does not need to coordinate with others, leading to lower latency for topic creation and message publishing.
    - **Reliability**: The system's reliance on each peer to manage its own topics introduces a reliability concern. Without replication or backup mechanisms, the failure of a peer leads to data loss.

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7. Ideal Case for the Design

- **Ideal Case**: In the ideal scenario, all peers stay online, and topic distribution among peers is even. This leads to high performance with minimal communication overhead, low latency for message retrieval, and efficient management of topics.

- The indexing server is always available and provides fast topic discovery.
- Peers that create topics remain online, allowing subscribers to access them without issues.

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8. Worst Case for the Design

- **Worst Case**: In a worst-case scenario, some peer nodes hosting important topics go offline, causing service disruptions for other peers. Without topic replication, this leads to data unavailability. Additionally, if the indexing server goes down, no new topics can be discovered, which impacts the overall functioning of the system.
    - **Load Imbalance**: If popular topics are disproportionately hosted on a few peer nodes, those peers may become overwhelmed with requests, leading to slowdowns or crashes.
    - **Failure of Central Indexing Server**: If the central indexing server goes offline, no new peers can join the system, and no new topics can be discovered.

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9. Possible Improvements and Extensions

1. **Topic Replication**:
    - **Problem**: A peer going offline causes the topics it hosts to become unavailable.
    - **Solution**: Implement a replication strategy where topics are stored across multiple peer nodes. This ensures that if one peer goes down, another peer can take over topic management, ensuring high availability.
2. **Dynamic Load Balancing**:
    - **Problem**: Popular topics can cause load imbalance, leading to certain peers being overwhelmed while others are underutilized.
    - **Solution**: Implement a load-balancing mechanism that can dynamically reassign or mirror popular topics to other peers, reducing the load on any single peer.
3. **Decentralized Topic Management**:
    - **Problem**: Reliance on a central indexing server creates a single point of failure.
    - **Solution**: Move towards a fully decentralized system where peers can communicate directly with each other to discover topics. This would reduce reliance on the central server and improve fault tolerance.
4. **Caching Mechanism**:
    - **Problem**: Accessing messages from topics hosted on remote peers may introduce latency.
    - **Solution**: Implement a caching mechanism at the peer level. Peers can cache messages from frequently accessed topics to reduce access times.

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10. Conclusion

The design of the **P2P Publisher-Subscriber System** focuses on simplicity, performance, and scalability. By following a **Self-Storage Policy**, the system allows peers to create and manage their own topics without requiring global coordination. However, this design has certain trade-offs, particularly concerning reliability and load balancing. By implementing future improvements such as replication, dynamic load balancing, and decentralized management, the system can become more robust and scalable, ensuring better fault tolerance and performance in large-scale deployments.

This document describes the core aspects of the system's design and identifies the trade-offs made during development. Potential future improvements could address the weaknesses in the current architecture, particularly in terms of fault tolerance and load balancing.